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PRINCIPLES OF RADIATION AND CONTAMINATION CONTROL

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VOLUME TWO

PROCEDURES AND GUIDELINES
RELATING TO NUCLEAR WEAPON EFFECTS



BUREAU OF SHIPS NAVY DEPARTMENT WASHINGTON 25, D. C.

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PRINCIPLES OF RADIATION AND CONTAMINATION CONTROL

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BUREAU OF SHIPS NAVY DEPARTMENT WASHINGTON 25, D. C.

prepared by

U. S. NAVAL RADIOLOGICAL DEFENSE LABORATORY

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ACKNOWLEDGEMENT

We have received so much help from many persons working in many places throughout the years we have been compiling this book, that it would take another book to list them. To every one of them, our sincerest thanks.

To any of them whose words we have paraphrased or whose statistics we have lifted without specific acknowledgement - our apologies along with our thanks.

PRINCIPLES OF RADIATION AND CONTAMINATION CONTROL

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(P O R A C C)

This series of three volumes on the control of radiation and radioactive contamination originated in a field manual developed for the naval participants in nuclear weapons tests at the Pacific Proving Grounds. Thinking that it might be more widely useful, it has been revised somewhat and divided according to "need to know" of the potential readers. The subject matter is presented more completely as the reader progresses from one volume to the next. The scientific foundation, i.e., the nuclear physics and radiobiology, are developed only to the extent needed in facing the practical problems.

The scope of the three volumes is limited to the control of radiation and contamination relating to nuclear weapons effects, and it is applicable primarily to non-wartime situations, although some of the material would be applicable to wartime use. For guidance under tactical situations the reader is referred to such publications as Bureau of Ships Technical Manual (Chapter 90, Radiological Recovery of Ships after Nuclear Weapons Explosions), and Radiological Recovery of Fixed Military Installations (NAVDOKS TP-PL-13). Criteria and procedures for controlling radiation and contamination relating to nuclear-powered ships are not contained in this manual but are contained in Radiological Controls for Naval Nuclear Propulsion Plants (NAVSHIPS 389-0153)(Classified).

Volume I is for persons working where there is radiation or using radioactive materials. It contains a general introduction to the physics of radiation and the biological effects that make it dangerous to health, together with techniques for measuring radiation and minimizing the chances that it will injure anyone. It should by itself meet the essential requirements of many persons.

Volume II is for those with special responsibility in regard to radiation, relating to nuclear weapons effects. It develops in more detail the fundamentals given in Volume I.

Volume III contains data needed to conduct training courses for which Volume II might serve as a textbook. It should be referred to when what is given in Volume I or even in Volume II seems insufficient.

VOLUME II

PROCEDURES AND GUIDELINES RELATING TO NUCLEAR WEAPON EFFECTS

Preface

This volume aims to provide necessary background and technical knowledge needed by those whose responsibility for radiation protection extends to others besides themselves. It has particularly in mind those who have to train radiological monitors. As a textbook, it should prove to be fitted to students with a high school education. It repeats many of the things told in Volume I, giving them a more detailed or quantitative treatment. It aims at a well-rounded coverage of radiation protection wherever it may be needed, not only in military operations but also around reactors, etc., with the methods of control adapted to each situation and enough science to make it understandable.

Satisfactory instruments and methods for field measurements are described in some detail. The material is treated quantitatively in a manner suitable for field requirements without going beyond simple arithmetic. The maximum permissible dose and maximum permissible concentrations as recommended by the AEC and National and International Commissions on Radiation Protection are set up as standards. The medical consequences are described for exposures of various degree.

Volume II could serve as a textbook for training officers, monitors, managers, and others responsible for radiological safety. Questions are included for self study and to assist instructors in preparing class examinations.

VOLUME II
PROCEDURES AND GUIDELINES
RELATING TO NUCLEAR WEAPON EFFECTS

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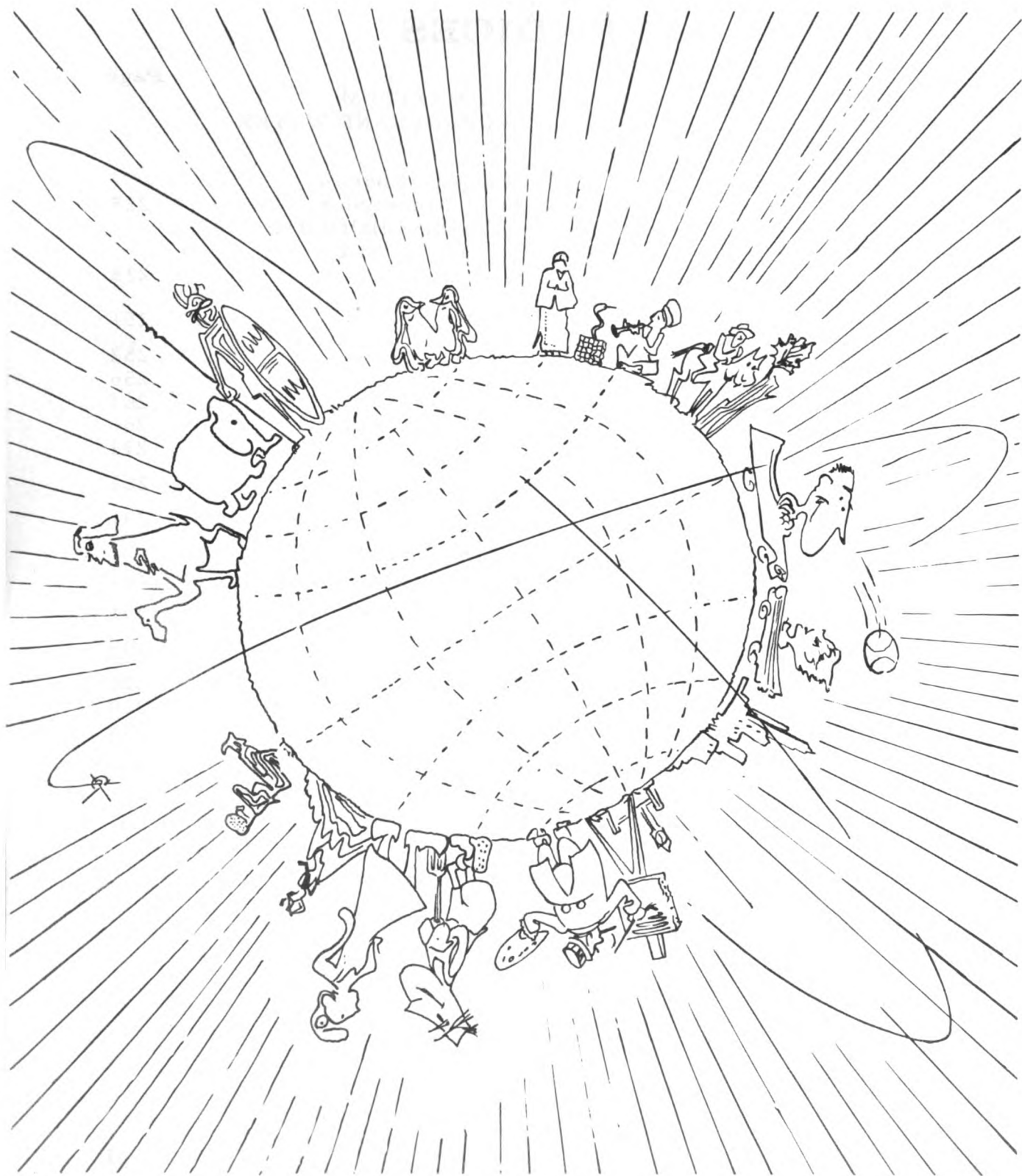
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CHAPTER

1

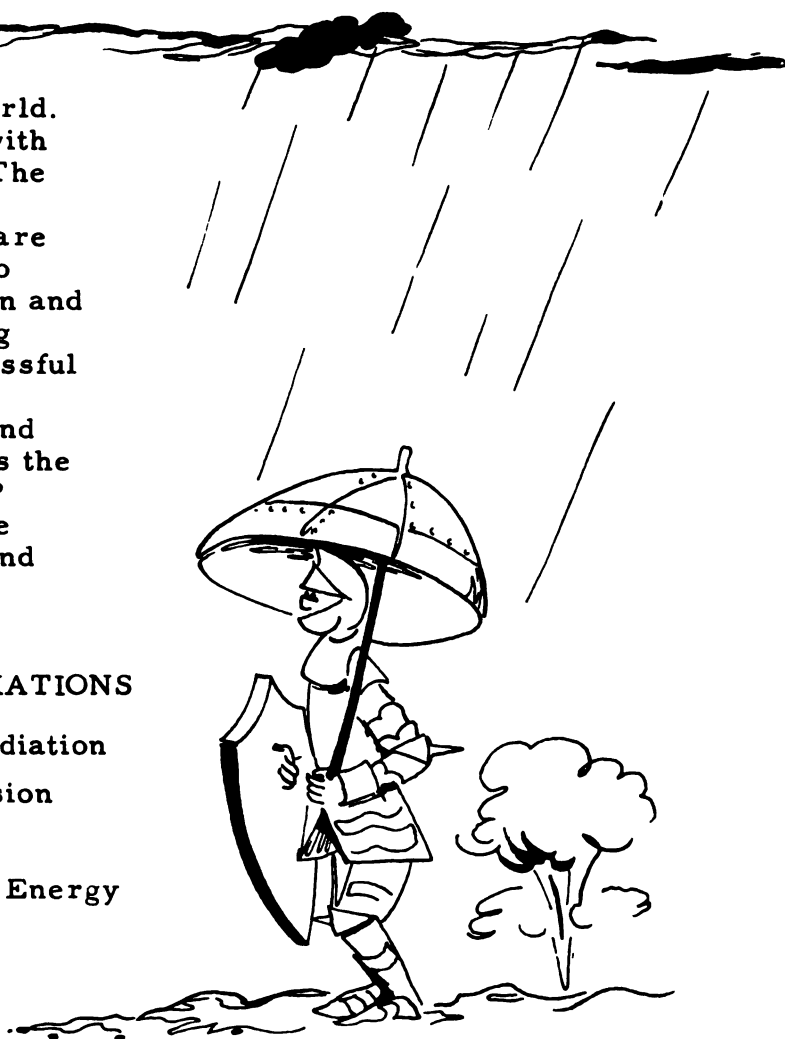
INTRODUCTION TO THE PROBLEM

Man lives in a radioactive world. He is constantly bombarded with radiation from outer space. The food he eats and the water he drinks contain minerals that are radioactive. As we move into the "ATOMIC AGE", radiation and radioactive isotopes are being produced by man. The successful application of nuclear energy depends upon understanding and controlling radiation. This is the problem. How do we solve it? First, we must find out where these radiations come from and how they are used.

SOURCES OF IONIZING RADIATIONS

- ① Natural Background Radiation
- ② Nuclear Weapon Explosion
- ③ Radioactive Fallout
- ④ Applications of Atomic Energy

Research
Industrial
Medical
Agricultural



Each of the above sources will be discussed briefly in the following pages so that the reader may become familiar with the problem.

1 NATURAL BACKGROUND RADIATION

Natural background radiation levels are important because they are used as a yardstick for evaluating the biological effects of radiation. Thus, the National Academy of Sciences's summary report on the biological effects of atomic radiation, in the report of the committee on genetic effects, illustrates the use of natural background levels as the basis for estimating the genetic "doubling dose." It has been estimated that the amount of radiation required to double the rate of spontaneous mutations already occurring is probably between 30 and 80 roentgens (received by the gonads prior to conception in addition to what comes from the natural background).

AVERAGE NATURAL BACKGROUND RADIATION
DOSE RATE TO THE SKELETON

Source of Radiation	Millirem Per Year
External Radiation	
Cosmic Rays	30
Local Gamma Rays	60
Internal Radiation	
Potassium-40	8
Radium-226	12
Mesothorium	12
Radium-D	12
Carbon-14	0.1
	<hr/> 134.1
Fallout	0.1 to 10 mrem/yr

The NATURAL RADIOACTIVE GASES in the atmosphere are radon and thoron that diffuse up from uranium and thorium minerals in the earth's crust. The amount varies a great deal from place to place. Their radioactive daughters are solid and form an AEROSOL. All these give a radioactivity amounting to 10^{-14} $\mu\text{c/cc}$ to 10^{-11} $\mu\text{c/cc}$. This is a lower concentration than the radon locked up in an ordinary radium dial wrist watch would produce in the air inside the Radio City Music Hall.

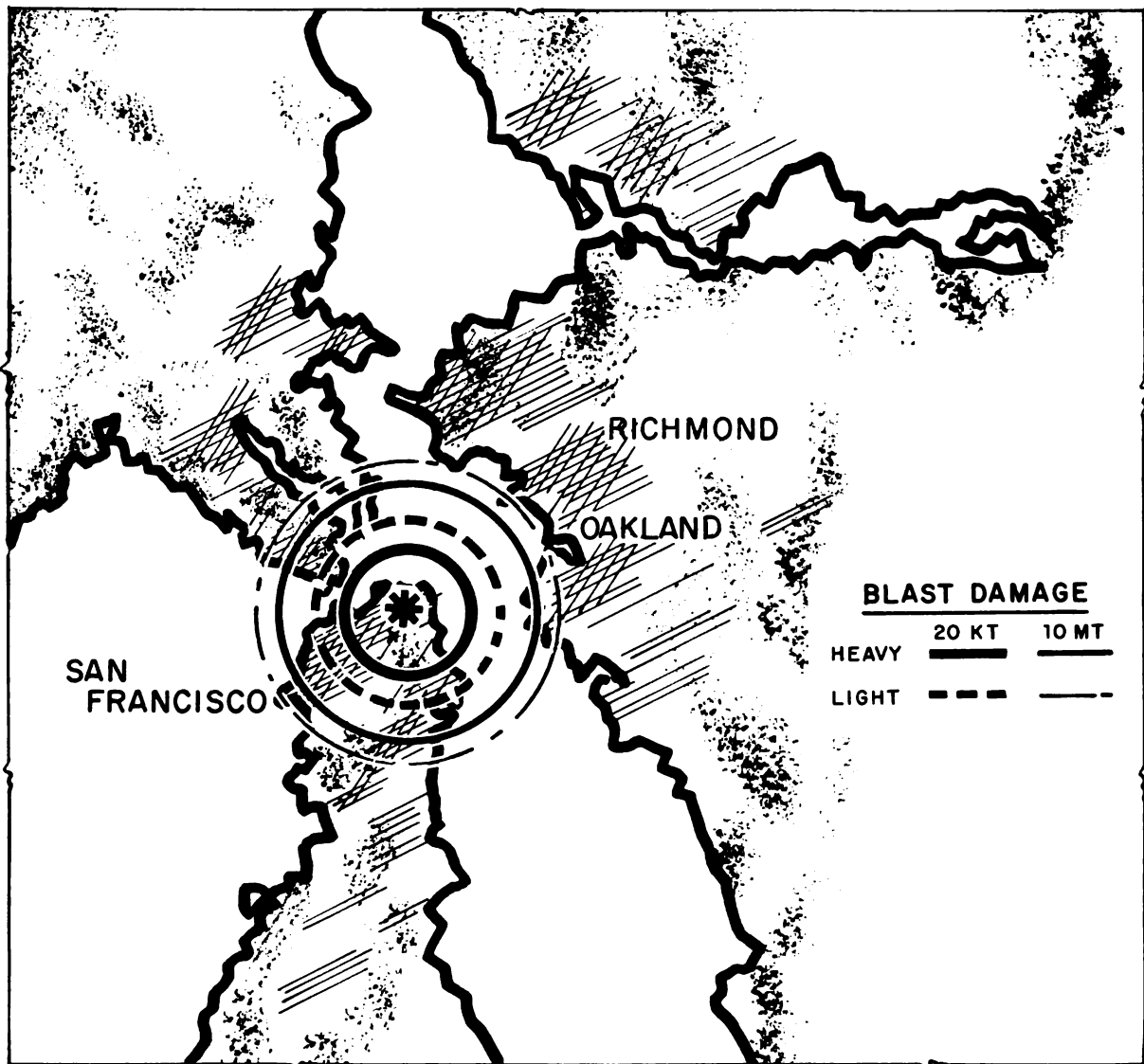
2 NUCLEAR WEAPON EXPLOSION

According to General Curtis E. LeMay, almost 1,500,000 sorties were flown against Germany during World War II. A total of 2,700,000 tons (2.7 megatons) of bombs were dropped. This vast output of destructive energy, which destroyed or heavily damaged scores of large cities, key industries, 20 to 30% of the homes, and killed or wounded many hundreds of thousands of persons, can now be matched in destructive force by a single hydrogen bomb.

The atomic bomb dropped on Japan was equivalent to 20 kilotons of TNT. This multiplied the explosive force of the blockbuster (1 ton TNT bomb) by 20 thousand. A 2 megaton hydrogen bomb is 100 times larger still. Two million tons of TNT would cover a football field to about the height of the Empire State Building. The "blockbuster" now has become a "city pulverizer."

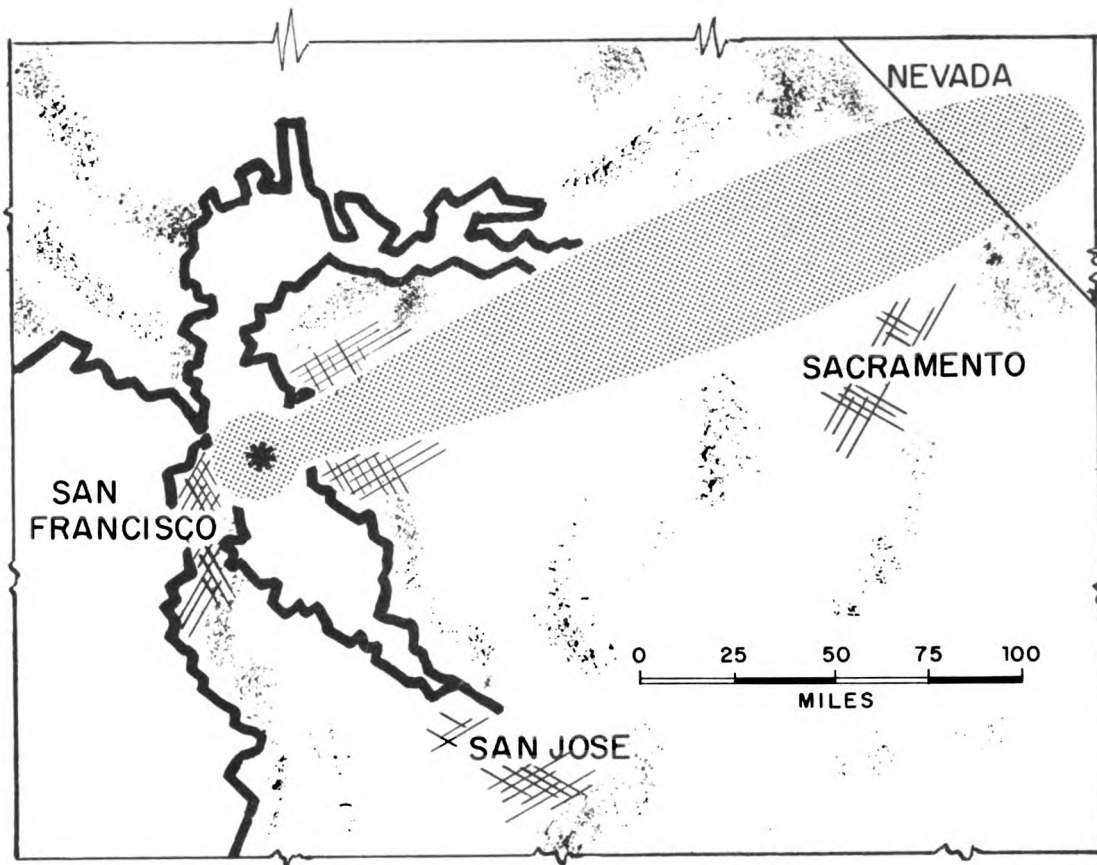


One Plane..... One Bomb..... One City



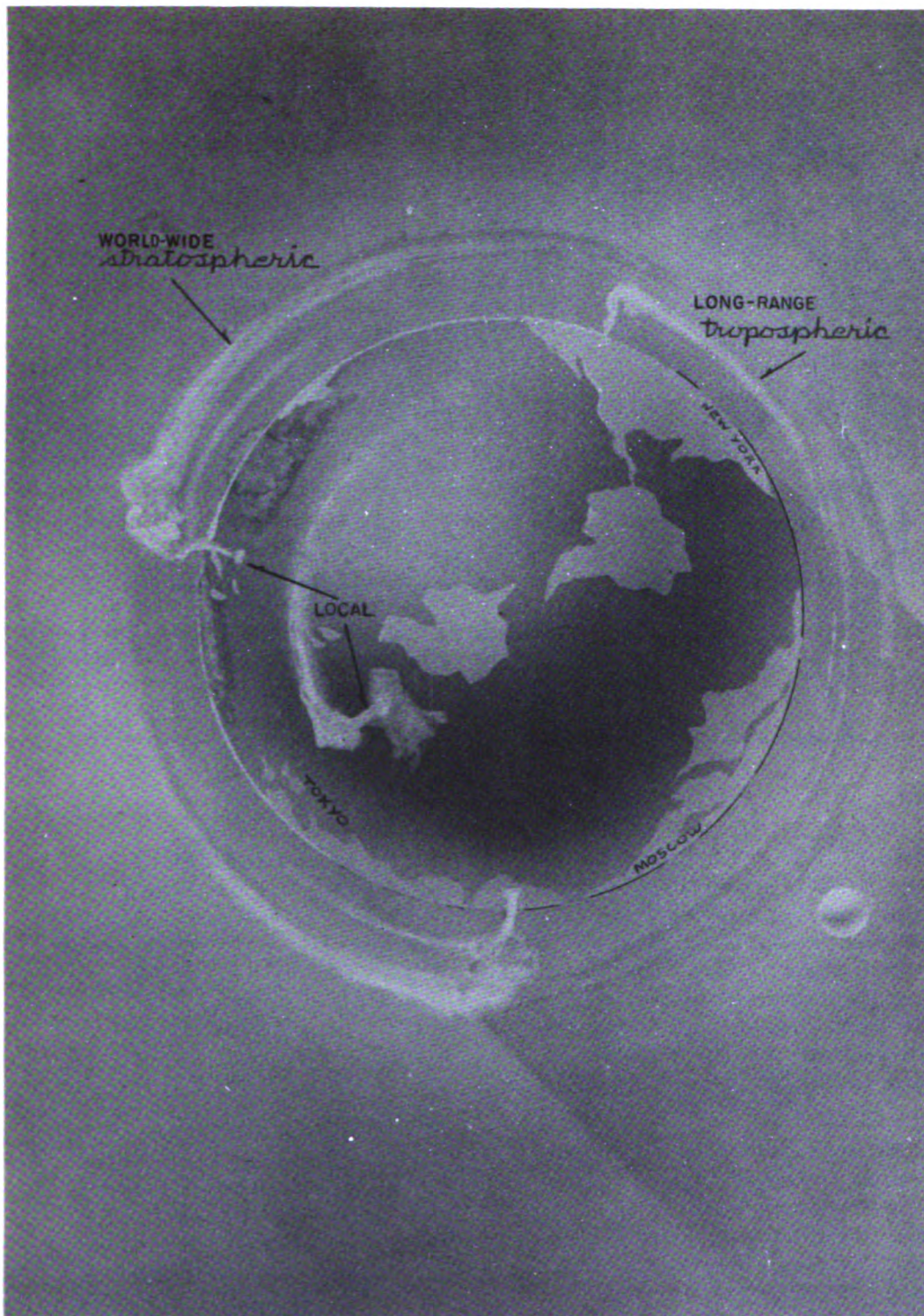
BLAST. The above illustration indicates the blast damage that would be produced if a 20 KT atomic bomb and a 10 MT hydrogen bomb were dropped over the San Francisco-Oakland Bay Area.

THERMAL. The ball of fire has a temperature of a million degrees in the center. As it expands, the radiation is as though you had enough suns to fill an equal portion of the sky and this does not cool off for a second or two. This heat radiation starts fires. Even if the blast wave blows some of them out, you still have fires started by broken wiring, gas mains, etc. In a city, a fire storm is inevitable.



INITIAL RADIATION. The gamma rays produced at the instant of explosion are mostly absorbed in the bomb casing but the neutrons produced then and for a few seconds after do get out. The gamma rays from the fission products come in an enormous quantity at first, lessening rapidly with time. A mile and a half from a 5 MT bomb, 50% of the initial gamma radiation is received in four seconds. The neutrons are absorbed in the air and even from a large bomb do not reach out more than about one and one-half miles. The gammas from a 5 MT bomb could be lethal at two miles.

All of these effects are mutually reinforcing. That is, a person who escaped serious thermal injury might die from a heavy dose of radiation; a person who was protected from the direct blast might be killed by flying debris or burned to death in a secondary fire. All the radiations are attenuated by distance, but the neutrons and the gammas are also attenuated by absorption in air. Therefore, at 5 or 10 miles from a big bomb, the thermal and blast effects dominate the picture. Though the 20 MT bomb is a thousand times more powerful than the 20 KT bomb dropped over Hiroshima, the damage from the blast extends out only 10 times as far.



THE SOUTHERN HEMISPHERE IS FAIRLY CLEAN SINCE MOST OF THE BOMB TESTING HAS BEEN NORTH OF THE EQUATOR.

3 RADIOACTIVE FALLOUT

Radioactive fallout results from a nuclear explosion. Fallout, consisting of radioactive fission products mixed with debris from the earth's surface, is thrown up into the atmosphere by the weapon detonation. The larger and heavier particles fall to earth at short distances from the point of detonation. The finer and lighter particles linger, travel with the wind and remain in the atmosphere for long periods of time. For megaton weapons fired near the ground, fallout may be divided into three classes: LOCAL, LONG-RANGE, and WORLD-WIDE.

LOCAL FALLOUT results from the larger and heavier particles which fall to the earth within the first few hours to a few days after the blast occurs. The illustration on Page 5 shows the local fallout which would result if a weapon were detonated in the San Francisco Bay Area. Prevailing winds determine the shape of the area covered by the fallout. The cigar-shaped fallout pattern used in the illustration is patterned after the March 1, 1954 Bikini megaton detonation. Fallout from the Bikini detonation covered a 7000 square mile area.

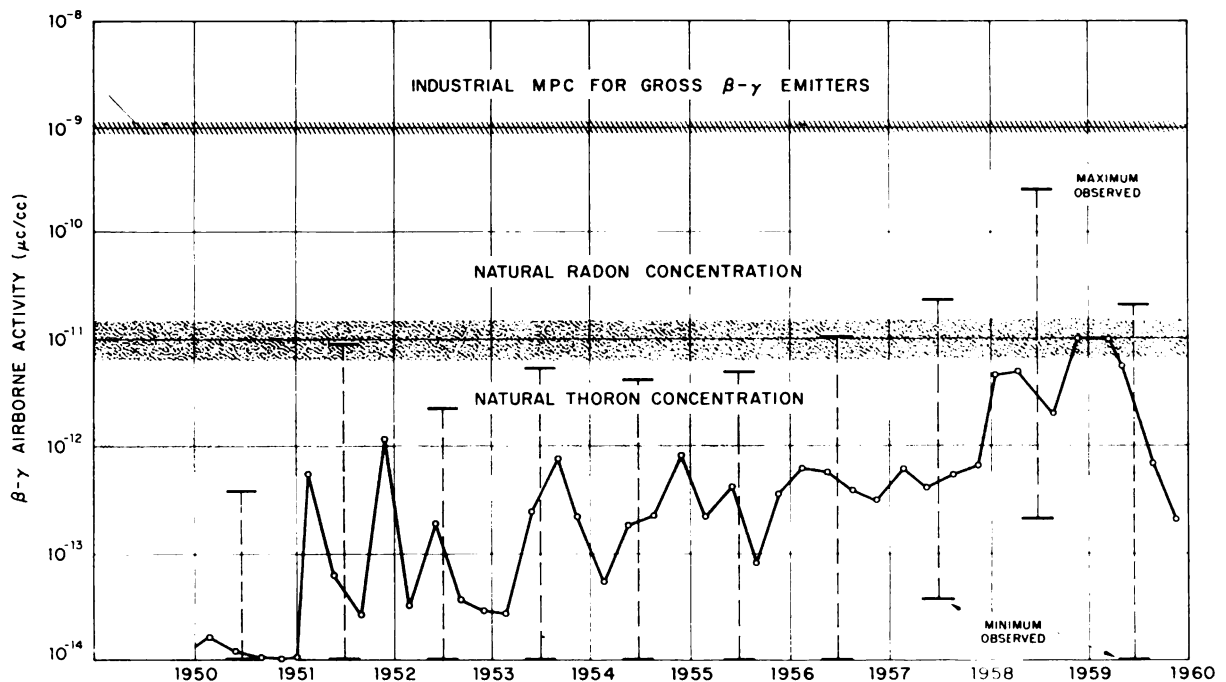
LONG-RANGE FALLOUT is due to smaller particles which go high but remain in the troposphere (less than 50,000 ft). They fall slowly or are washed down by rain or snow. These particles may make several trips around the world before they settle to the earth's surface weeks later in the same general latitude as the weapon detonation. **FALLOUT FROM KT-SIZED WEAPONS GENERALLY DOES NOT ENTER THE STRATOSPHERE.**

WORLD-WIDE FALLOUT (half or more of the total contamination produced by a MT weapon) results from the finely divided material which reaches the stratosphere and remains there for several years. This finely divided material slowly drops from the stratosphere into the troposphere and gradually falls to the ground. It has been concluded that the stratospheric storage time varies significantly with the altitude and the latitude of the initial stabilized clouds from nuclear tests. Estimated residence times are six months to one year for Soviet tests; one to two years for equatorial tests in the lower stratosphere (typified by REDWING) ; and five to ten years for the CASTLE test.

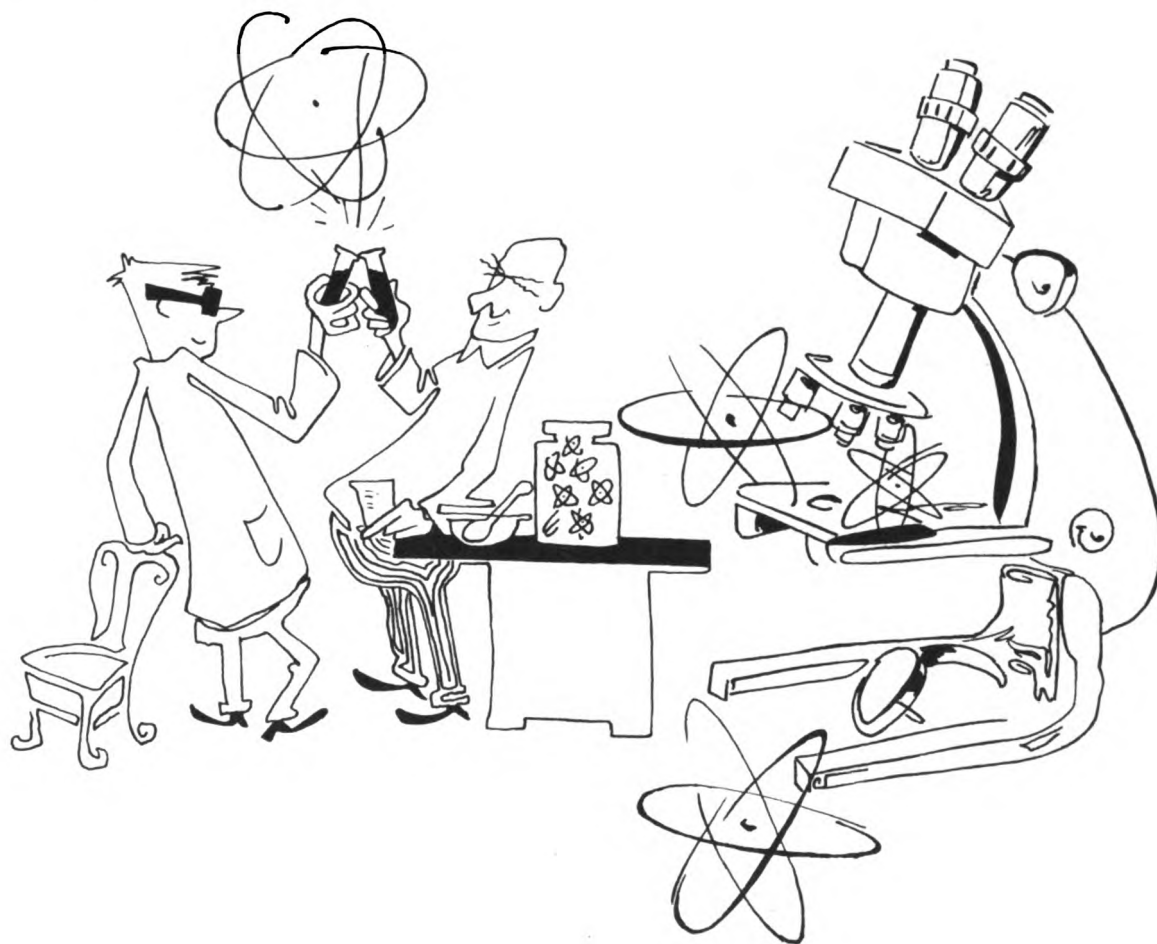
FISSION-PRODUCT CONTAMINATION IN EARTH'S ATMOSPHERE

The following graph illustrates the quarterly average fission-product activity in the atmosphere in the San Francisco Bay Area, as well as the natural thoron and natural radon concentration. There was hardly any fission-product activity in the atmosphere until after some big bombs had been tested. Most of the activity is fairly short-lived and probably never got into the stratosphere. The longer-lived airborne material which enters the stratosphere drifts with the prevailing winds from West to East. It tends to stay in about the same latitude at which the bomb was tested.

QUARTERLY AVERAGE FISSION-PRODUCT AIRBORNE ACTIVITY IN THE SAN FRANCISCO BAY AREA



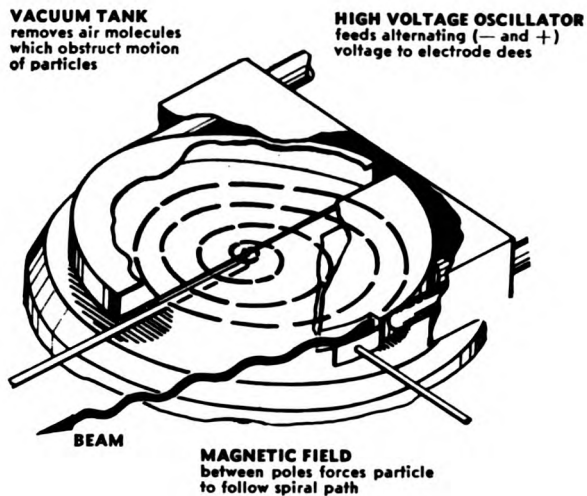
Prior to 1958, the average concentration of airborne fission products in the Bay Area was well below the natural level of radon activity and about equal to the natural thoron concentration. It should be noted that during the last quarter of 1958 the man-made radioactivity in the air was about 1% of the maximum permissible concentration for continuous exposure to undetermined mixtures of beta-gamma emitters.



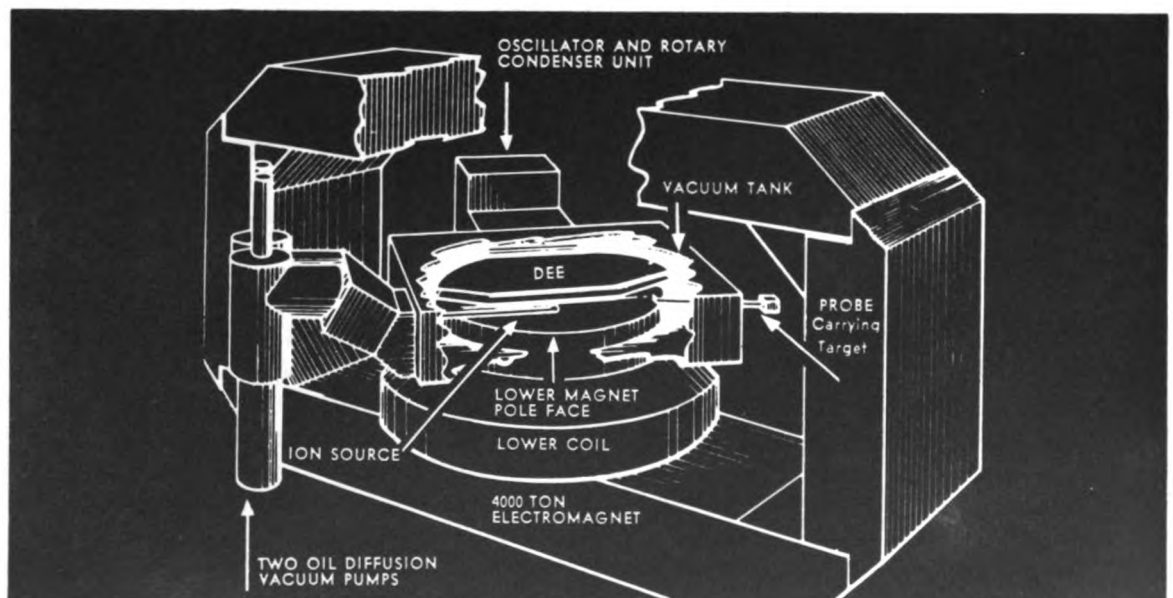
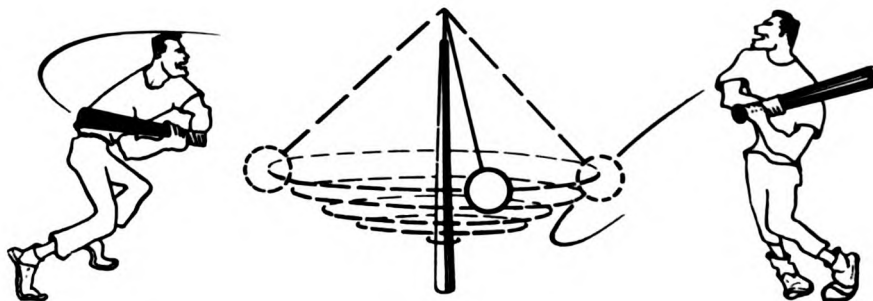
RESEARCH Radiation and radioactive isotopes have become very important tools to the research worker. Radioactive isotopes are used as tracers to follow complicated processes and as sources of radiation to measure and study materials and how they react.

Of particular importance are the machines of special design which are used to produce ionizing radiation. X-ray machines have been used for a long time. Nuclear particle accelerators are used to produce high-speed electrons, protons, neutrons, alpha particles, etc. These are all ionizing radiations. They are similar to radiations emitted by radioactive material except that the latter continue at their natural rate whereas the machine can be turned off. Radioactive material emits ionizing radiation in diminishing amounts until it has all decayed to a stable isotope.

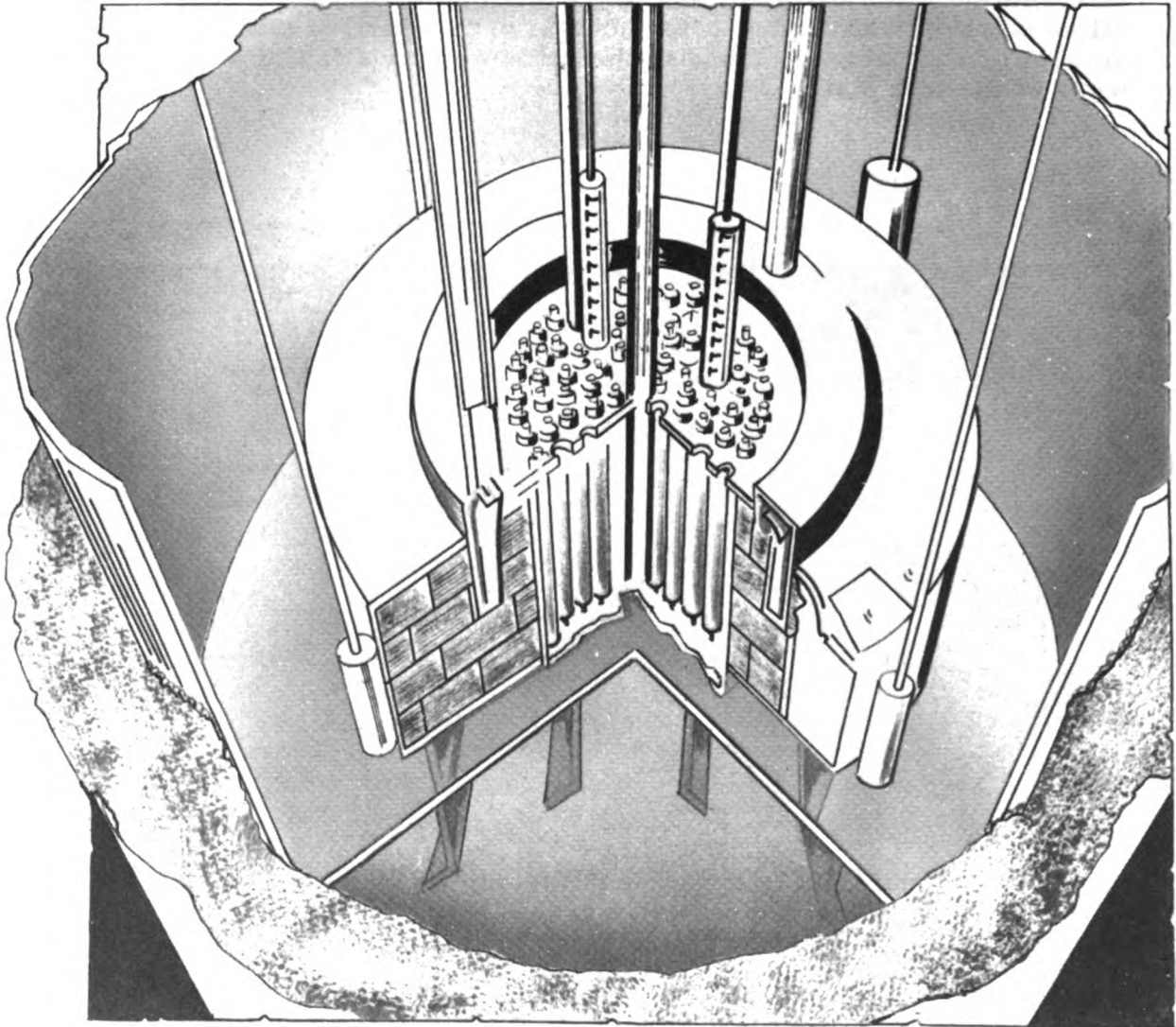
THE CYCLOTRON: A PARTICLE ACCELERATOR



A particle being accelerated in a cyclotron is analogous to a ball fastened by a string to the top of a pole. The ball is batted every half turn, thus increasing its speed and its energy. As its speed increases it follows a spiral path, moving outward from the pole. If the batters were to strike the ball as frequently as a particle being accelerated in the 184 inch cyclotron, they would have to strike it 20 million times per second.

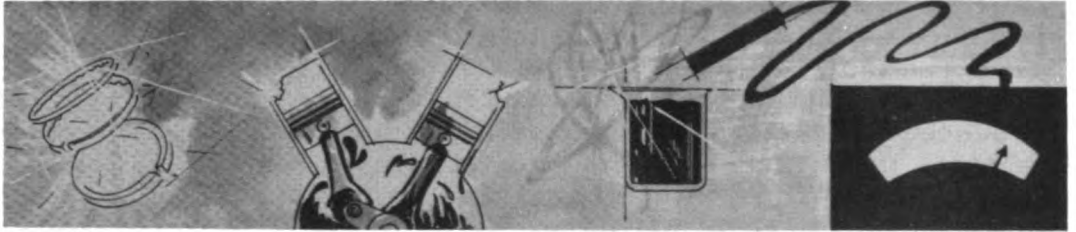


The tremendous amount of energy which is released in a nuclear reaction is put to work by controlling the rate of liberation of this energy. The device in which this controlled reaction takes place is called a REACTOR. The reactor is an important and flexible research tool. It can be used as a radiation source to study the effects of radiation on animals and materials. The neutrons that are produced in reactors can be used to produce many kinds of radio-isotopes that are very useful tools for the scientist. The reactor also produces large quantities of heat that may be converted to useful electrical or mechanical energy.



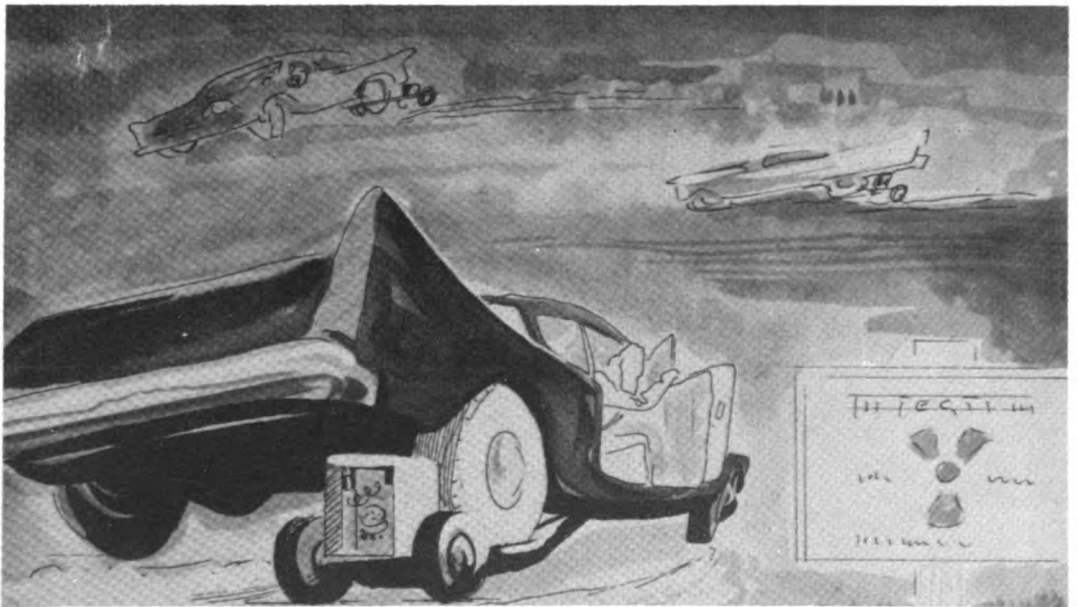
INDUSTRIAL APPLICATIONS

ENGINE WEAR



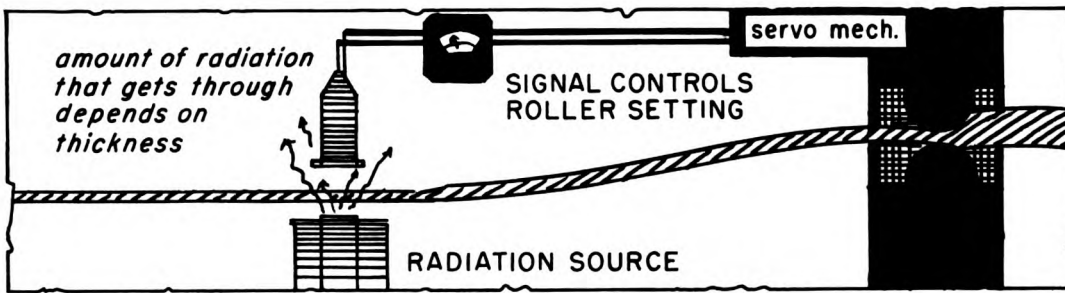
Piston rings are made radioactive by neutron bombardment in a reactor and then installed in a test engine. After operation of the engine, the oil is removed and analyzed for content of radioactive material. The amount of radioactivity found in the oil is an indication of the rate of wear of the test piston ring.

TIRE WEAR



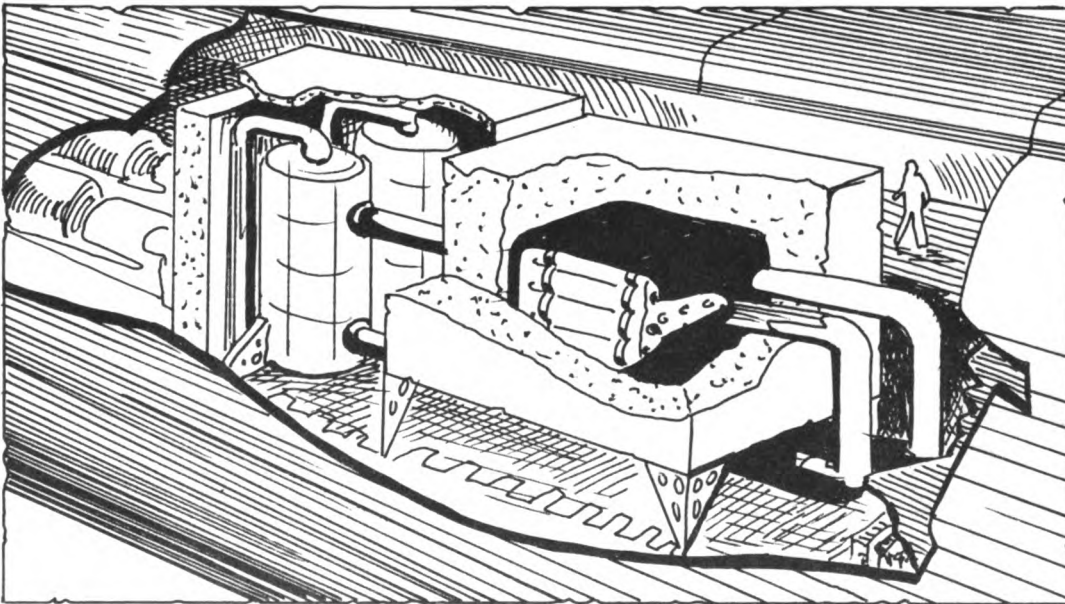
Radioactive material is mixed with the rubber to be used as tire tread. The decrease in the radioactivity of the tire is an indication of how fast a particular tread or type of rubber is wearing.

BETA THICKNESS GAUGE



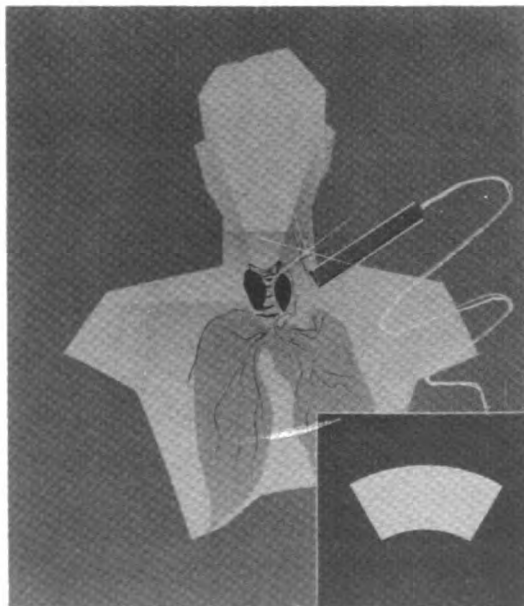
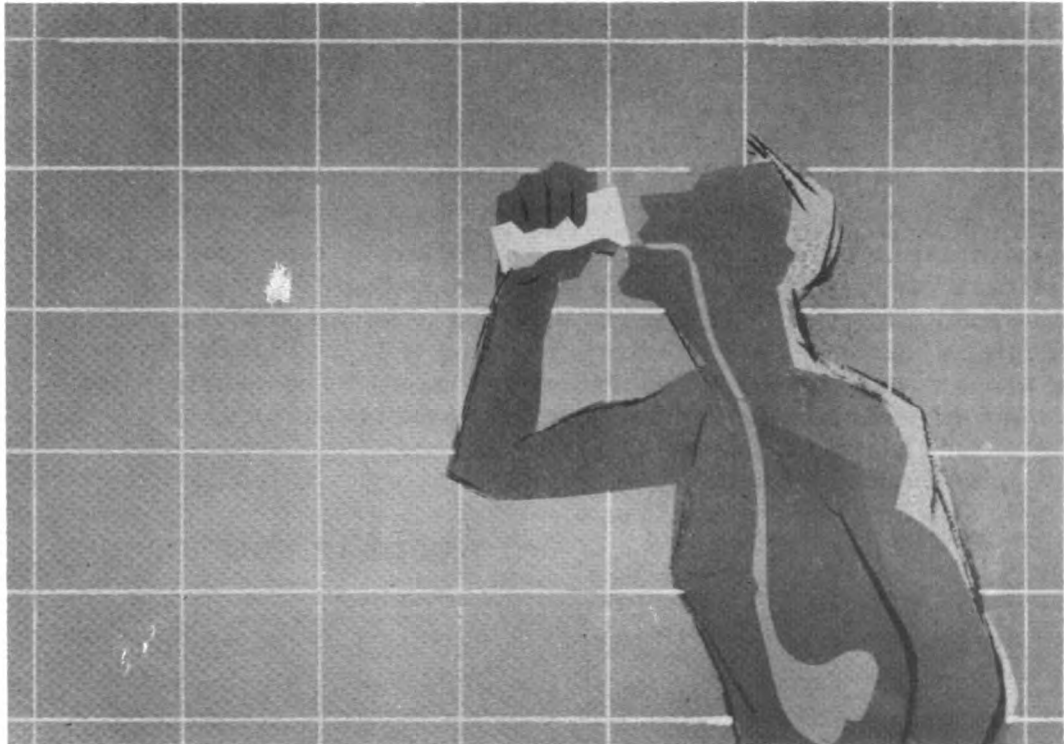
Thickness of paper or metal sheets is controlled by transmission of beta particles through the sheet. A radiation detector is coupled to the mechanism controlling the roller spacing. As the metal or paper sheet becomes thicker, the detector indicates less radiation transmission and signals the roller control mechanism to move the rolls closer together which in turn reduces the sheet thickness.

NUCLEAR PROPULSION



The above cutaway shows the reactor, biological radiation shield, and the reactor power plant of the USS NAUTILUS. The heat from the fissioning nuclei is used in the place of an oil fire to make steam in the boiler. The turbines produce electricity to drive the boat. The NAUTILUS completed 60,000 miles of cruising with its initial fuel load of fissionable material.

RADIOACTIVE IODINE- I^{131} FOR THYROID DIAGNOSIS AND THERAPY

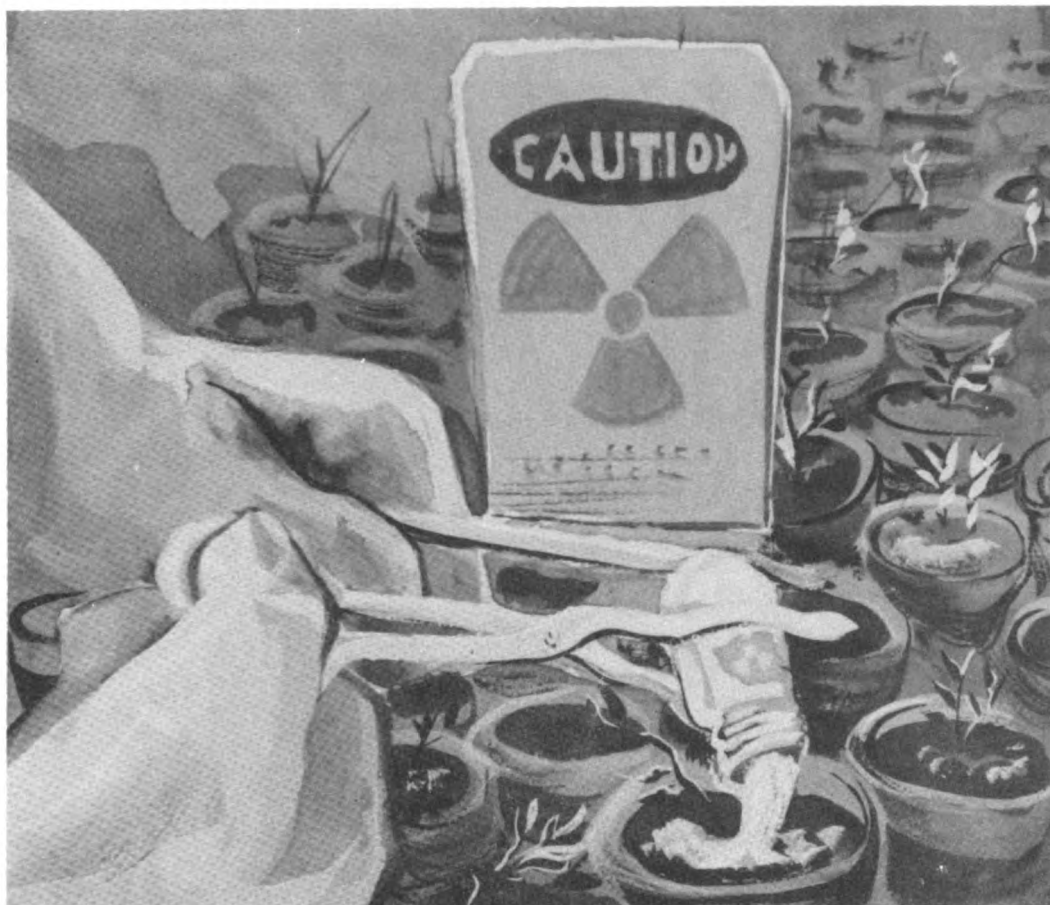


Radioactive Iodine - I^{131} with a half-life of 8 days is used for diagnosing and treating disease of the thyroid. Radioactive iodine labels the stable iodine in the blood and shows, by its activity in the neck, how fast the thyroid is using iodine. Large doses of radioactive iodine can irradiate the thyroid enough to stop its function.

X-RAY MACHINES



The X ray is one of the most powerful diagnostic tools that the physician has. X rays are emitted when the electrons evaporated from the incandescent cathode of the X-ray tube are accelerated by high voltage and strike the anode. The X-ray picture is really only a kind of silhouette produced by the slight or strong stoppage of the X rays by the flesh and bones. The calcium in the bone casts a strong shadow which looks white on the film (negative).



In agricultural research, radioisotopes have been used ever since they first became available. Their greatest value has been in plant-growth studies where they have enabled scientists to determine how various chemicals are absorbed and used by growing plants. By tagging chemical substances with radioisotopes, botanists have been able to measure the efficiency of both fertilizers and weed killers. In addition, isotopes are being used to trace the metabolic processes of cows and the migrations of mosquitoes. Radioactive forms of certain metallic elements - like molybdenum, zinc, and iron - are being fed to plants to find out how much of these trace elements are required for normal growth. Nuclear energy has been employed in rodent and pest control. Rodents and other pests have been tagged with radioactive isotopes to keep track of their comings and goings so that they may be brought under control.



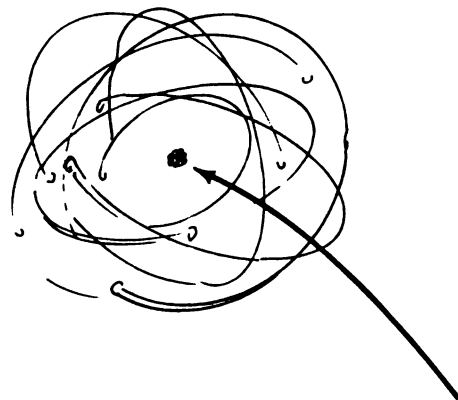
Various nutrients containing radiocarbon are injected into the animal which then exhales radioactive CO_2 into a gas mask. The rate at which radioactive CO_2 is exhaled shows how fast the cow's body uses the injected compounds.

BASIC SCIENCE

INSIDE THE ATOM

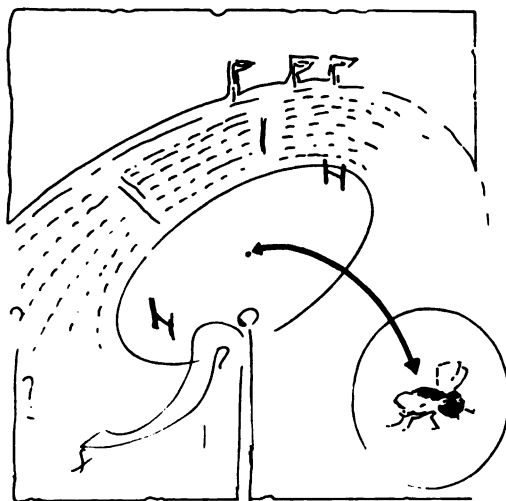
Atoms are tiny indeed - much too tiny to see. Trying to see an atom with light waves (1000 times as long as the atom) is something like trying to hear the echo from a mustard seed.

The picture of an atom as a little solar system with planets (electrons) held in orbits around the sun (nucleus) by gravity (electric attraction) is pretty fancy. Since we cannot see the atom we can imagine it as we will. But electrons differ from planets in that their orbits are only average positions and that they can jump from one orbit to another when the atom radiates energy or absorbs it.

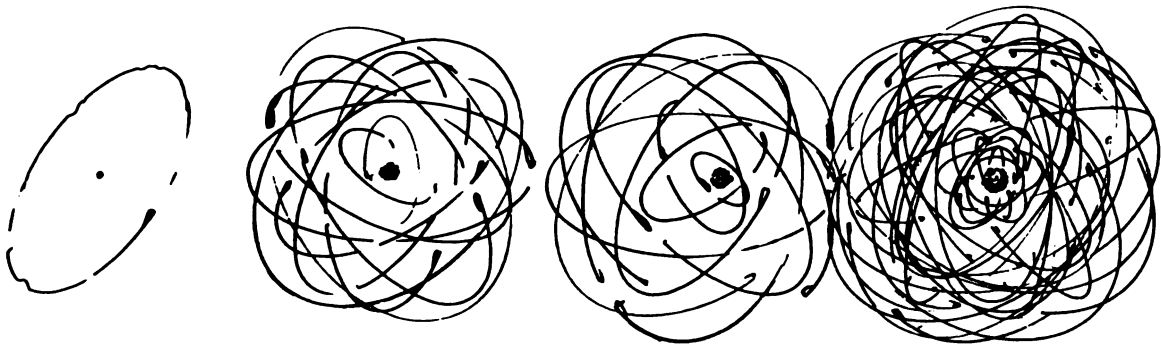


The nucleus of the atom is made up of neutrons and protons. They have about the same weight (mass) but the proton carries a positive charge while the neutron carries none. The electrons carry a negative charge and are so light (though they might be big and fluffy) that it would take 1840 of them to equal the weight of one proton or neutron. For every proton in the nucleus, there must be one orbital electron if the atom is to be electrically neutral.


The atom's nucleus is extremely tiny and very dense (99.95% of the atom's weight is in the nucleus). Because of its great density, a nucleus as large as the one shown at the top of this page would weigh as much as 8000 battleships. The concentration of its mass in the tiny nucleus leaves most of the atom practically empty space. If an atom were expanded to the size of a football stadium, the nucleus would be no larger than a housefly. Adding or removing a proton or neutron to or from the nucleus makes it into a different atom.



ATOMIC WEIGHT



Hydrogen 1	Oxygen 16	Oxygen 18	Uranium 238
Protons 1	Protons 8	Protons 8	Protons 92
Neutrons 0	Neutrons 8	Neutrons 10	Neutrons 146
Mass No. 1	Mass No. 16	Mass No. 18	Mass No. 238

and the number of electrons  whirling around each of these nuclei are

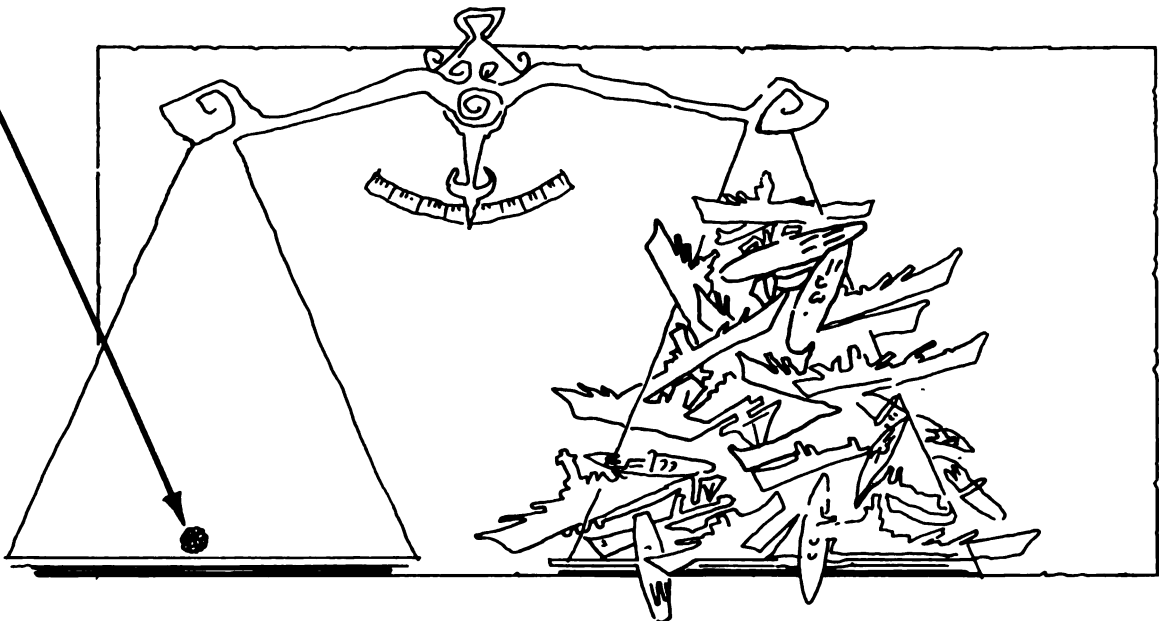
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(8)

(92)

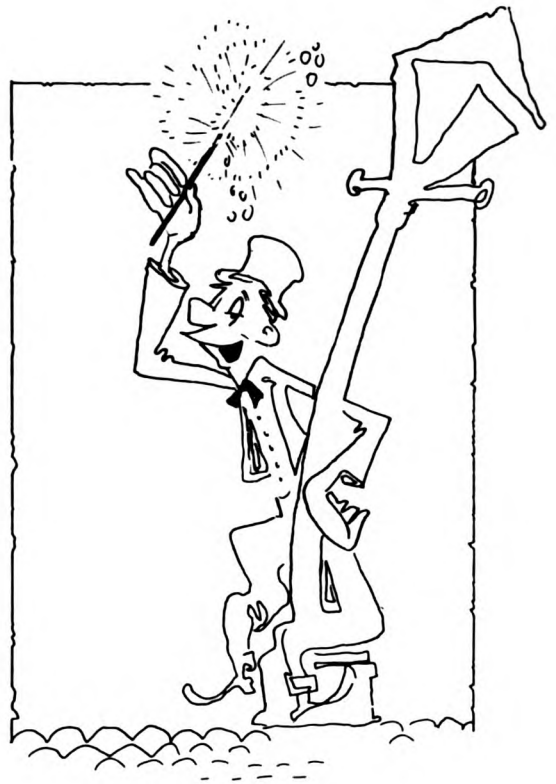
The atom is the smallest indivisible part of an element. An **ELEMENT** is what it is because of the particular number of **PROTONS** in the nucleus. But an element may have atoms with various numbers of neutrons in the nuclei. When atoms have the same number of protons, but not the same number of neutrons, they are still the same element but are different **ISOTOPES** of that element.



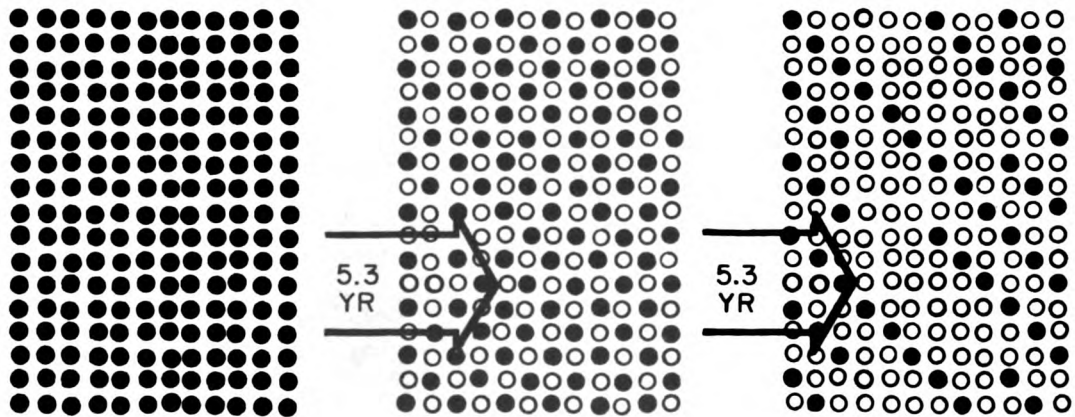
THE ATOMIC NUCLEUS IS TINY BUT HEAVY FOR ITS SIZE.

RADIOACTIVITY

Many isotopes are unstable, that is they disintegrate spontaneously, emitting nuclear particles. That is why we call them RADIOACTIVE. The radiations given off may be alpha particles, α ; beta particles, β ; or gamma rays, γ . (When radiation is of very high energy it is looked upon as a particle and given the name PHOTON.) Radium, a naturally occurring radioisotope, has a very long-lived radioactive ancestor, uranium-238; otherwise there wouldn't be any radium left in the world. Short-lived isotopes come from the decay of long-lived ones or are man-made in nuclear reactors and bombs and with high voltage accelerators.



Every radioactive isotope is characterized by its emitted radiations and the time it takes for a quantity of radioactive material to decay to one-half of its original amount is called its half-life, $T_{1/2}$.

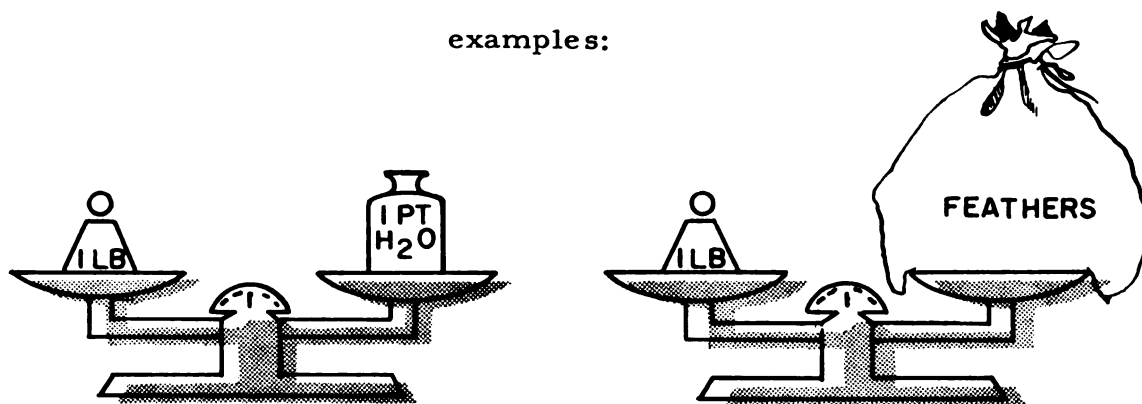


RADIOACTIVE CO^{60} ● AND STABLE NI^{60} ○.

The half-life of an isotope is the major factor that will determine whether the radioactive material will be found in a minute or a relatively large mass. Since neither size nor mass (weight) can describe the amount of radioactivity present, the term CURIE is used. The CURIE is that amount of radioactive material that disintegrates at the rate of 37 billion atoms per second. The longer the half-life ($T_{1/2}$) the more atoms it takes to provide a given amount of activity (because every disintegration transmutes an atom) and the longer the supply will last. Therefore, the half-life is a good measure of the rate of decay. The greater the chance of the atoms disintegrating (shorter $T_{1/2}$) the smaller the number of atoms required to produce a given amount of activity.

A POUND is a pound no matter what it looks like.

examples:



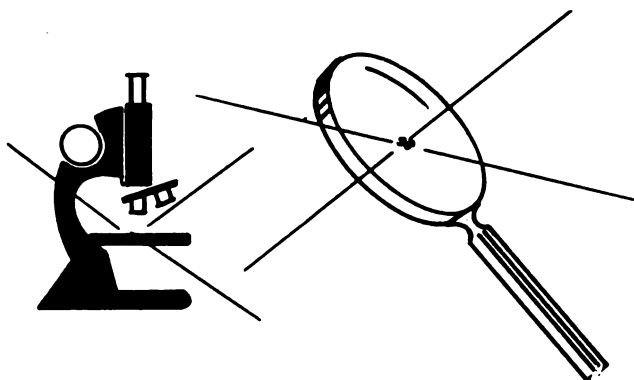
A CURIE must contain enough atoms to provide 37 billion atomic disintegrations per second

examples:

ONE CURIE La-140
($T_{1/2}$ ABOUT 2 DAYS)

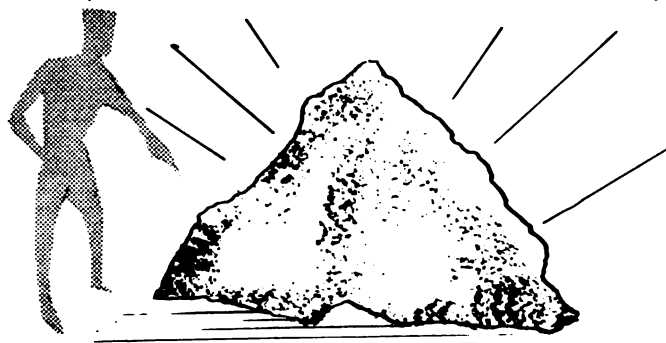
ONE CURIE Ra-226
($T_{1/2}$ ABOUT 1600 YEARS)

ONE CURIE U-238
($T_{1/2}$ ABOUT 3 BILLION YEARS)



0.0000000006 ounce
(1.8 micrograms)

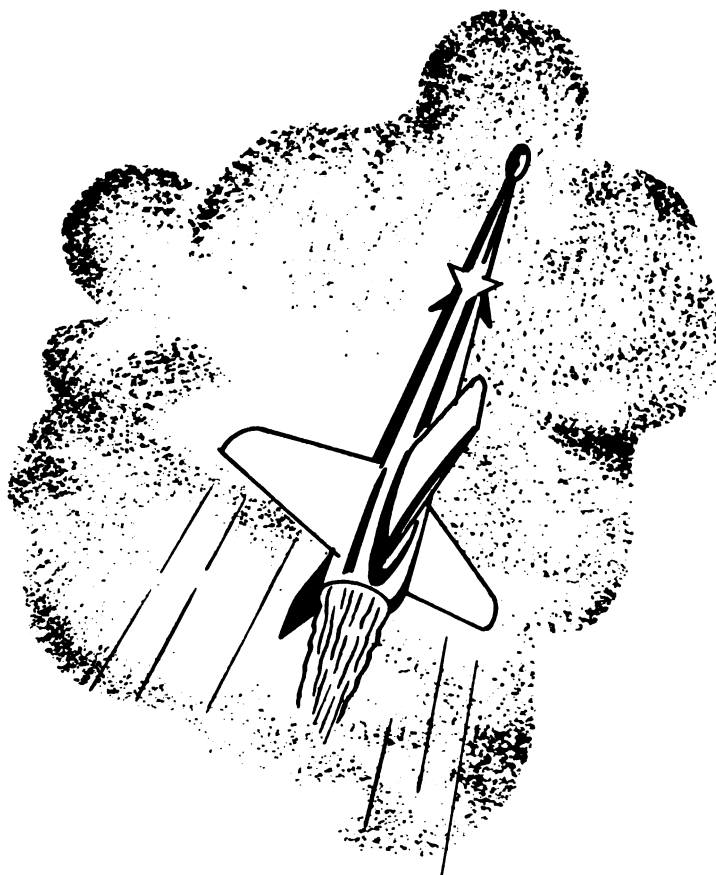
0.04 ounce
(1 gram)



3 tons
(2,980 kilograms)

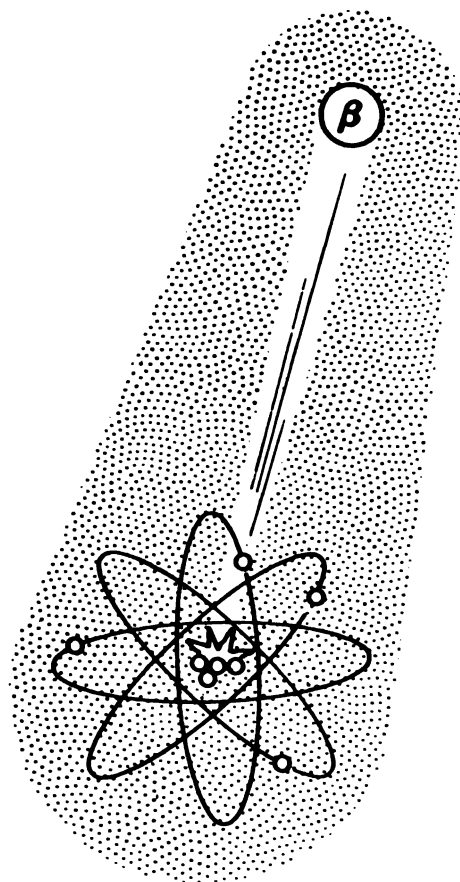
The radiations emitted from radioactive materials are characterized by both their type (alpha, beta, gamma) and their energy, which is measured in electron volts (ev) or in millions of electron volts (Mev). Thus beta particles may be said to have an energy of 2 Mev from one radioactive isotope and 0.5 Mev from another.

THE ROCKET



Energy measured in
FOOT POUNDS

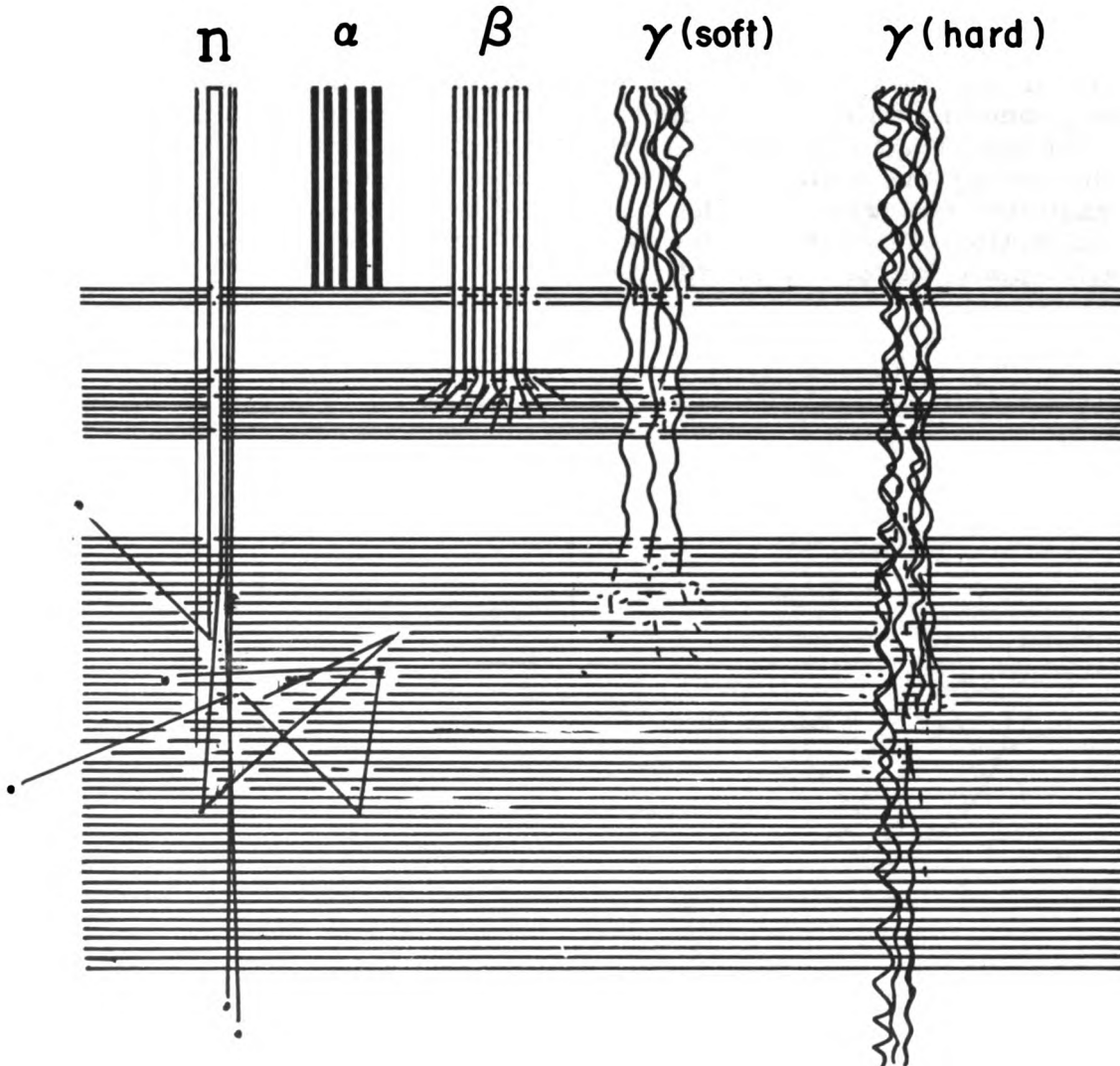
THE BETA PARTICLE



Energy measured in
ELECTRON VOLTS

As the energy of the rocket is measured in foot pounds, the kinetic energy of the beta particle (and other ionizing radiations) is measured in ev or in Mev.

Just as every radioactive material has a characteristic half-life, so every type of radioactive emission has its characteristic half-value layer (HVL). This is the thickness of a particular material that will stop half of the radiation from going through. The higher the Mev of the emission, the larger the HVL. If the HVL is greater than 1 mm of soft tissue, the health physicist calls it PENETRATING or HARD. Otherwise, it is SOFT RADIATION.

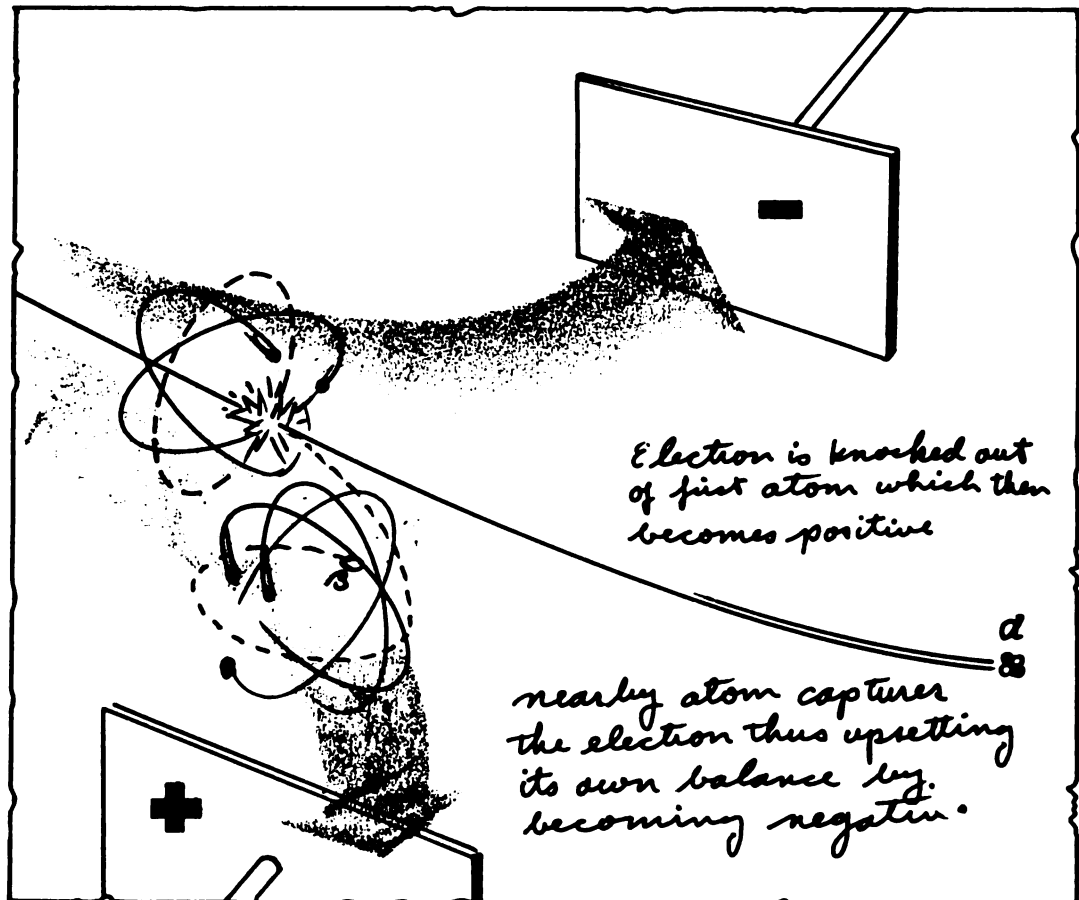


ILLUSTRATING PENETRATION OF α AND β AND HARD AND SOFT γ RAYS. NEUTRON RAYS ARE ALSO PENETRATING RADIATION.

IONIZATION

Radiations (α , β , γ) give up their energy principally through the process of ionization. Ionization breaks neutral atoms into electrically charged ions. A neutral atom has as many orbital electrons as it has protons in its nucleus. When one of the electrons (negatively charged) is removed, it leaves the atom with one excess positive charge. The atom thus becomes a positive ion. The free electron attaches itself to another atom, making a negative ion. Thus, ions are formed in pairs.

The intensity of the radiation can be measured by collecting the ions - hence producing an electric current. Ionization is the principal process for detecting radiation. We must not forget that this is measuring the energy the radiation is leaving behind and not the total energy the radiation is carrying. The following figure shows the formation and collection of ions by the interaction of radiation going through a parallel-plate ionization chamber.



BIOLOGICAL EFFECTS OF RADIATION

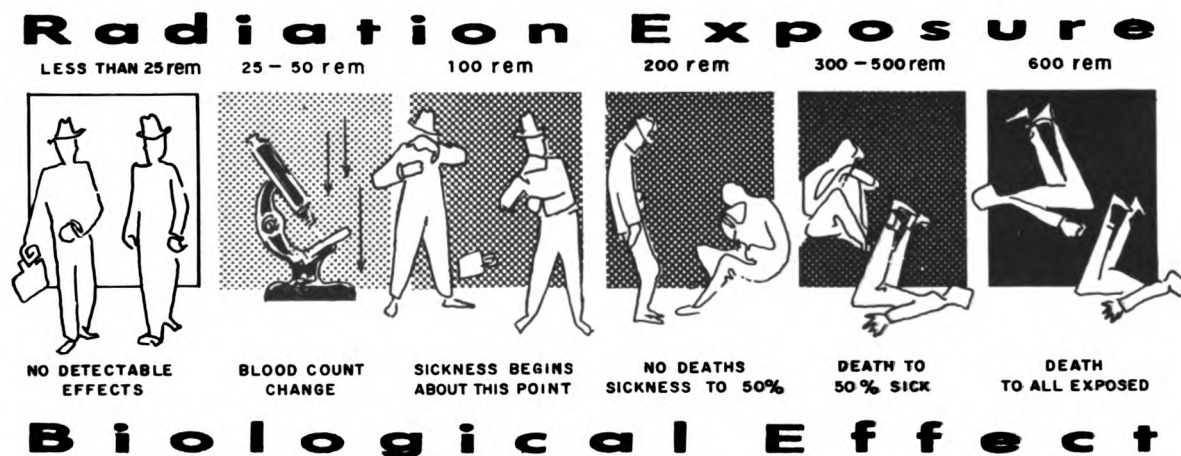
Ionizing radiations passing through the body injure the living cells. The amount of injury depends on the amount of ionization, but some cells and some organs are much more sensitive than others. Moreover, the same exposure does not produce the same amount of ionization all through the body. The inner organs get less than the skin does. How much less depends on how penetrating the radiation is. Also, the biologic effect depends on whether the exposure happens in a short time or is spread out over many days or weeks.

The amount of ionization, i. e., the amount of energy absorbed per gram of tissue, is measured in RAD. Roughly speaking, the exposure to one roentgen gives a dose of one rad.

Because some radiations, like neutrons and alpha particles, do more damage than X rays for the same amount of ionization, we have another practical unit called the REM. The dose of one rem is equal in biologic effect to an X-ray dose of one rad. For γ and β radiation, one rad equals one rem. It is important to note that radiations of low penetrating power (e. g., alpha and beta) affect only those tissues which are close to the source of the radiations.

Exposure to radiation involves short- and long-term effects. Whole-body doses of about 100 rem probably would cause occasional nausea in the first 24 hours. Exposure of the whole body to from 300 to 500 rem would produce nausea and weakness in the first 24 hours, followed by a latent period of 7 to 12 days, and then sickness with possible death to 50%. Higher doses are followed in a few hours or days by vomiting, diarrhea, fever, collapse and death shortly thereafter. Long-term effects (sequelae) are cataracts, leukemia, increased degenerative diseases, shortened life span, and genetic mutations.

An acute dose of radiation is one that is received in less than about a day. The following figure summarizes the effects of various acute doses of penetrating radiation covering the whole body.



SOFT RADIATION (beta and low-energy gamma)

Many radiations penetrate deeply into the body, but there are lots of radiations from machines run at low voltage and from fallout and from particular isotopes that penetrate into the skin and not much farther. They leave their energy in such a small thickness of tissue that it is very concentrated and a little goes a long way in producing injury. But the injury is limited to a tissue that has great ability to heal itself. An amount of radiation that would be fatal if it affected the internal organs may give only a blistering burn if it is all beta radiation or very low-energy X ray. (Beta radiation, and alpha too, that starts inside the body from internal contamination is another matter.) The amount of radiant energy absorbed in the basal layer of the cuticle is the critical **SURFACE DOSE**.

Beta-exposure is very hard to evaluate precisely. Beta radiation cannot be measured in roentgens. What the radiac reading gives is the absorbed dose in the radiac. Then you have to know how much the skin is like the radiac and how soft the radiation is if you want to know the absorbed dose in the skin.

Table of ACUTE Effects from Radiation Absorbed
in the Skin (basal layers of the cuticle).

BETA RAD DOSE*	EFFECT
0 - 600	No acute effect
600 - 2,000	Moderate early erythema (reddening of skin)
2,000 - 4,000	Early erythema under 24 hours - skin breakdown in 2 weeks
4,000 - 10,000	Severe erythema in less than 24 hours - severe skin break- down in 1 to 2 weeks
10,000 - 15,000	Severe erythema in less than 4 hours - severe skin break- down in 1 to 2 weeks
15,000 - 100,000	Immediate skin blistering (less than 1 day)
* Estimated dose required in less than 1 week	

ACUTE RADIATION SYNDROME

Radiation can kill. Biological effects of radiation must be understood before trying to put nuclear energy to work. The following are photographs of a man who received a whole-body dose of about 600 rem of hard (penetrating) gamma and neutron radiation in addition to over 20,000 rads of soft radiation.



UNITS OF MEASUREMENT

Ionizing radiations are divided into two classes:

- ① **PENETRATING RADIATIONS** (half-value layer greater than 1 millimeter of soft tissue)
- ② **SOFT RADIATIONS** (half-value layer less than 1 millimeter of soft tissue).

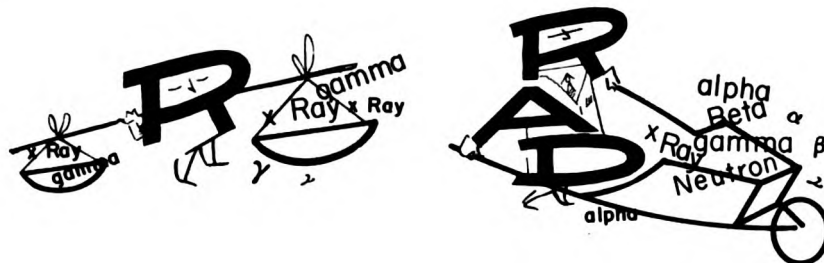
Fast and thermal neutrons and gamma rays are penetrating radiations which deliver their energy throughout the whole volume of the body. Beta particles penetrate only the outer layers of the skin; alpha particles are stopped in the cuticle before they reach the living basal layer. When radioactive material is taken into the body, the alpha particles, instead of being the least effective, are the most effective. In this case, beta particles and gamma rays are quite comparable in effect, except that some of the gamma rays may escape without being absorbed.

We have three units for measuring radiation (1) the ROENTGEN (R) to measure the exposure, (2) the RAD for the energy delivered where it counts and (3) the REM, which is the rad corrected for biologic effectiveness.

- R - The amount of X or gamma radiation that is capable of producing 2,100,000,000 pairs of ions per cm^3 of air. This amounts to 1.6×10^{12} pairs per gram of air. To make these ions requires about 87 ergs. Soft tissue exposed to the same radiation absorbs about 93 ergs per gram.
- REP - Formerly used to mean an absorbed dose of 93 ergs per gram, from beta radiation especially, but is now replaced by the internationally adopted rad (nearly the same size).
- RAD - The absorbed dose of 100 ergs per gram of any matter and can be used for any ionizing radiation.
- REM - The biological dose, or the exposure leading to an absorbed dose, equal in biological effect to one rad of ordinary X rays. It differs from the rad by a factor called the RBE (relative biological effectiveness). The rem applies to all types of radiation.

Various units are used for measuring radiation, but the PHYSICAL MEASUREMENTS of radiation must be CONVERTED to BIOLOGICAL EFFECTS upon man.

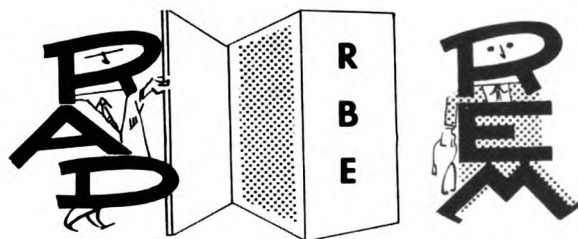
R - RAD



The ROENTGEN (r) is a unit of exposure that applies only to X rays and gamma rays. The absorbed dose in tissue is 93 ergs per gram from exposure to 1 r. This amount of absorbed dose used to be called 1 REP, but the term is now obsolete.

Since there are other types of radiation, such as alpha, beta, and neutrons, another unit of measurement must be defined. This new unit of absorbed dose is called the RAD. 1 rad is the absorbed dose of 100 ergs per gram of any matter and can be used for any ionizing radiation.

REM - RBE



$$\text{RADS} \times \text{RBE} = \text{REMS}$$

The rad is a physical measurement, but the dose in rads does not tell us the biological effect. The physical dose, corrected by a factor for the relative biological effect (RBE) in man, is a convenient unit and is called the REM.

Careful study and research have established limits or safety factors for the amount of radiation that the human body should receive.



The important unit is the rem because it signifies the effect of the ionizing radiations on man. ALL IONIZING RADIATIONS DO NOT PRODUCE THE SAME BIOLOGICAL EFFECTS ON MAN. Using the rad as a measure of the energy absorbed from the ionizing radiation and the rem as a measure of their biological effects on man, we can compare the RELATIVE BIOLOGICAL EFFECTIVENESS of the various ionizing radiations.

ONE RAD ABSORBED FROM	PRODUCES AN EFFECT OF	GIVING THE RBE FACTOR
ALPHA	10 REM	10
FAST NEUTRONS	10 REM	10
THERMAL NEUTRONS	3 REM	3
GAMMA OR X RADIATION	1 REM	1
BETA	1 REM	1

THE PROPER PERSPECTIVE

The exposure in field tests and industrial situations will usually result in absorbed doses ranging from thousandths of a rem (millirem) to less than 10 rem. **A PERSON WILL NEVER BECOME AWARE OF THE EFFECT OF A WHOLE-BODY PENETRATING DOSE OF LESS THAN 25 REM.**

The maximum permissible exposure (MPE) to ionizing radiation and the maximum permissible concentration (MPC) of radioactive isotopes which a man may receive are based on the premise that an exposure giving 5 rem in a year will do practically no harm.

When one is required to exceed the yearly MPE of 5 rem, the total dose during any calendar year should not exceed 12 rem - with the limitation that the individual's total lifetime maximum permissible dose (MPD) does not exceed $(N-18) \div 5$ rem. N is the person's age (greater than 18 years). For radiation workers it is convenient to establish a weekly MPE so that the 5 rem per year will not be exceeded unknowingly. Since the worker is allowed to receive 3 rem (of his yearly 5 rem) in a calendar quarter, intermittent operations are planned with a weekly MPE of 0.3 rem while continuous operations involving radiation exposures are based on 0.1 rem per week.

EXTERNAL VS INTERNAL EXPOSURE

The maximum permissible dose (MPD) is 12 rem per year. This MPL (maximum permissible limit) includes external dosage as well as internal dosage. If radioactive materials are taken into the body, these materials continuously irradiate the body until they have decayed to stable isotopes or are biologically eliminated. Therefore, it becomes important to prevent these radioactive materials from entering the body. The maximum permissible concentrations, MPC's, of the various radioactive materials have been set at levels that will not give a dose rate greater than 0.3 rem per week. These are given in Appendix A of this volume.

The dangers of internal contamination cannot be overemphasized. Once the contamination is inside the body, only biological processes determine the rate of elimination. For some radioactive materials, the biological half-life is very long. **ONE CAN WALK AWAY FROM AN EXTERNAL RADIATION SOURCE BUT CANNOT WALK AWAY FROM INTERNAL RADIOACTIVE CONTAMINATION.**

RADIOLOGICAL SAFETY FUNDAMENTALS

ASSESSMENT



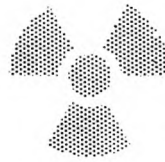
The utilization of nuclear energy and ionizing radiations has brought forth a new specialty in preventive medicine, **RADIATION HYGIENE**, and a new field of endeavor, **HEALTH PHYSICS**. Their ideals and activities are based on the concept of MPE's and MPC's.

It is the functions of **APPLIED HEALTH PHYSICS** or **RADIOLOGICAL SAFETY** to enable personnel to:

- ① understand the problems associated with the use of radioactive materials and radiation sources
- ② understand the use of equipment and facilities to minimize contact with radioactive materials and ionizing radiations
- ③ establish radiological safety procedures for the control of radiation and contamination

thereby assuring compliance with the established MPE's and MPC's.

Radiological safety demands a complete evaluation of every radiological situation (**ASSESSMENT**) so that areas of radiological hazard may be marked (**DELINEATION**) and unauthorized personnel kept out. Thus radioactive material can be prevented from irradiating or contaminating personnel or the environment (**CONTROL**).



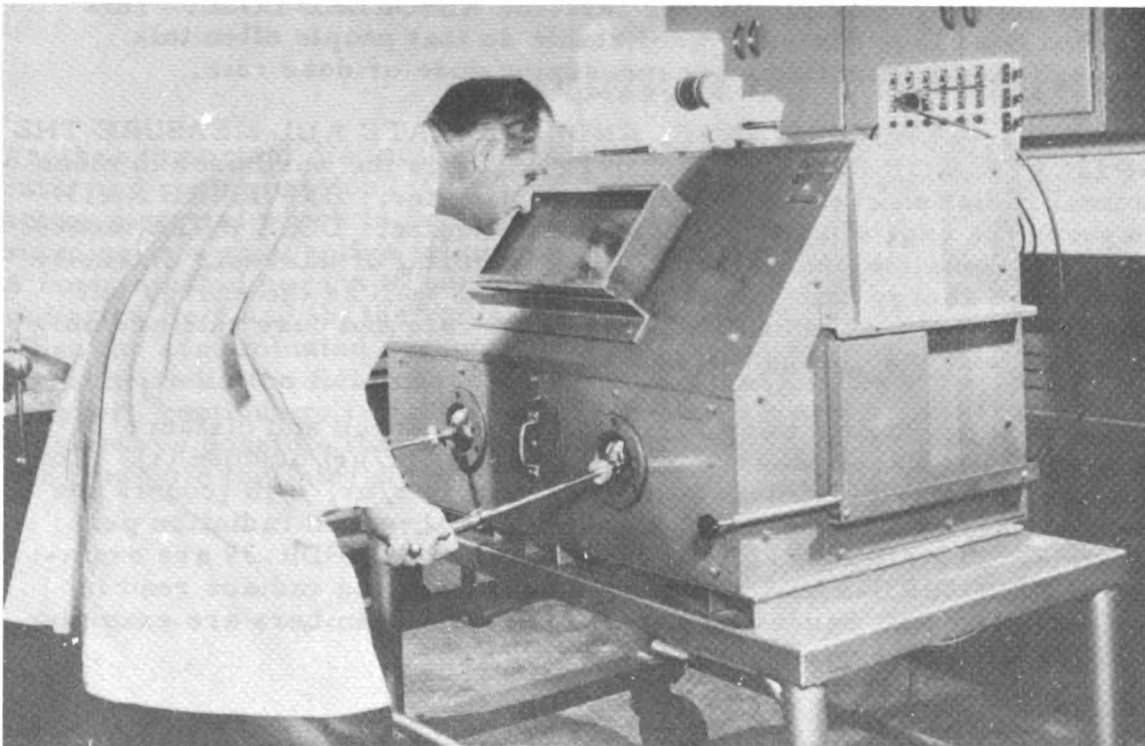
DELINEATION

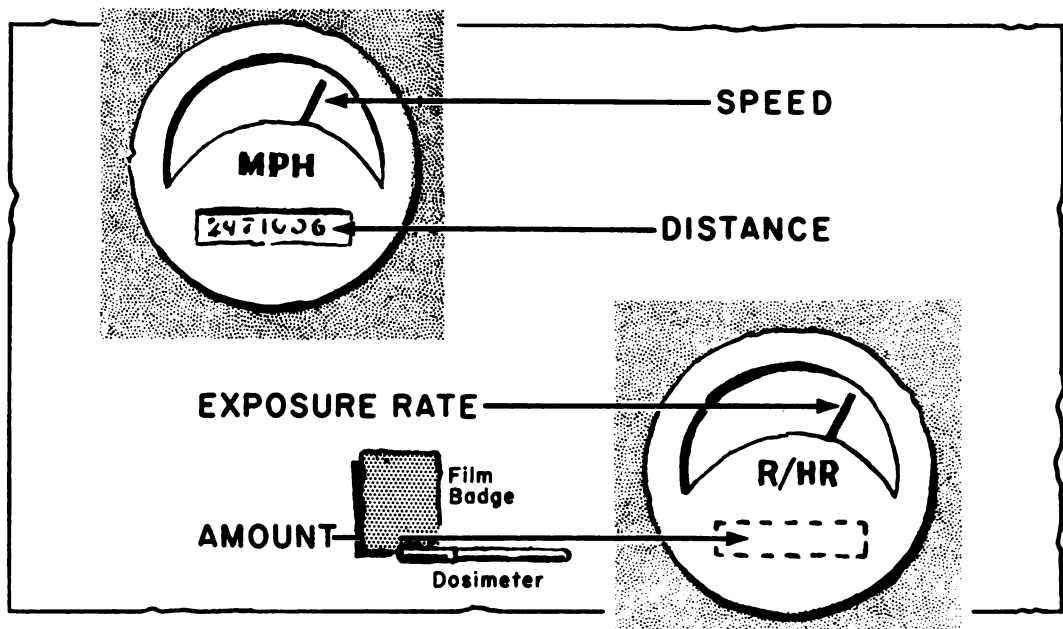
Radiological safety, the elimination or minimization of external and internal exposure to ionizing radiation, is a dynamic program which must never lose sight of the fact that radiological safety is a means to an end. That is, the job or the mission is the goal, and radiological safety is the means used to get the job done with maximum safety to personnel. In the laboratory or in industrial plants, operations and equipment are planned so that the least time is spent in dangerous situations, resulting in personnel exposures well below the established MPL's.

Time, equipment and manpower are more difficult to manage during missions or projects in field tests. This makes it mandatory for radiological safety personnel to have a thorough understanding of the situations so that their evaluations of the radiological problem will result in procedures that will minimize radiation exposure.

The MPE's and MPC's for field tests may have to be modified to allow accomplishment of the mission, but in no case does this modification allow more accumulated exposure of personnel than would be permitted in industrial situations for extended periods of time.

CONTROL



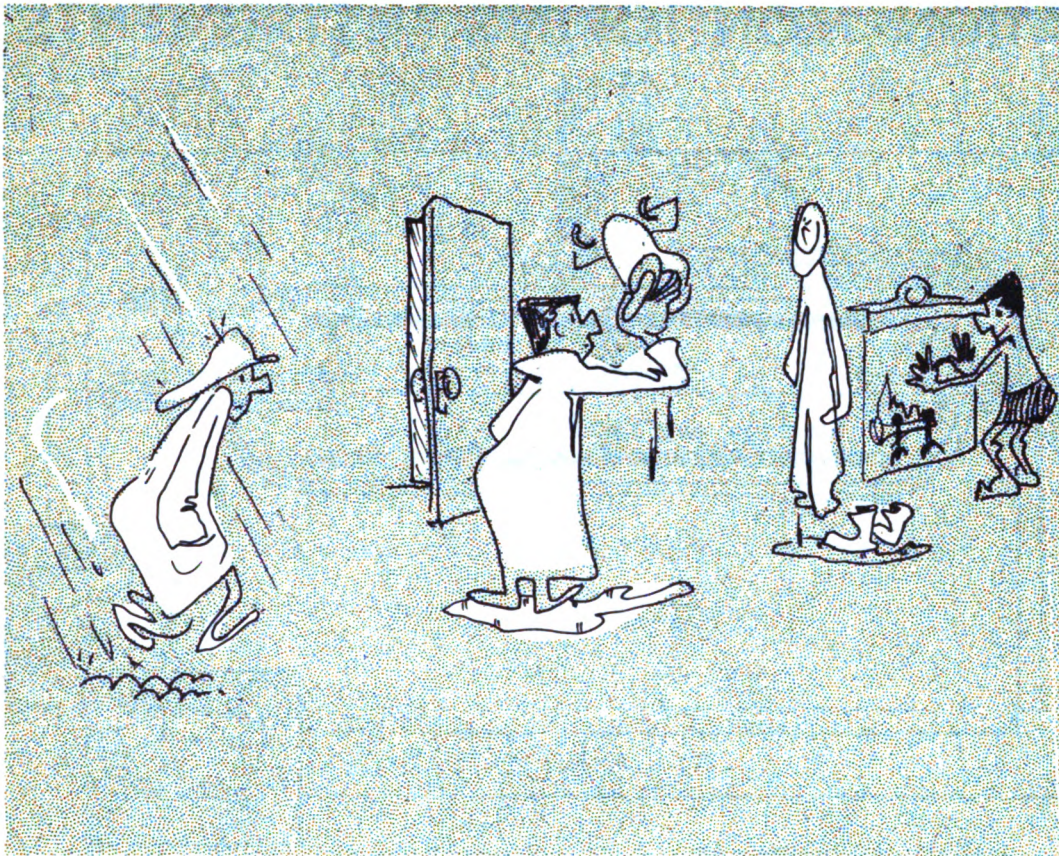


DOSE RATE AND DOSE

The two fundamental concepts in radiation monitoring are DOSE RATE and DOSE. The DOSE is the quantity or TOTAL AMOUNT of ionizing radiation energy absorbed (per gram). The DOSE RATE is the rate at which the dose piles up. The monitor usually measures the exposure rate which gives the level of dangers, the radiation field, and tells how much a person would be absorbing if he were exposed there. Radiacs actually measure EXPOSURE and NOT the ABSORBED DOSE. This absorbed dose is sufficiently predictable so that people often talk as though the instruments were measuring dose or dose rate.

INTENSITY, EXPOSURE RATE, AND DOSE RATE ALL MEASURE THE APPLICATION OF RADIATION. INTENSITY is the word used to mean the total radiation carried per square centimeter. EXPOSURE RATE measures the capability of the radiation to ionize. DOSE RATE measures its accomplishment in ionizing the material of interest. Intensity includes the energy that passes on through as well as the energy left behind in the form of ionization. Exposure rate and dose rate are only concerned with the energy left behind.

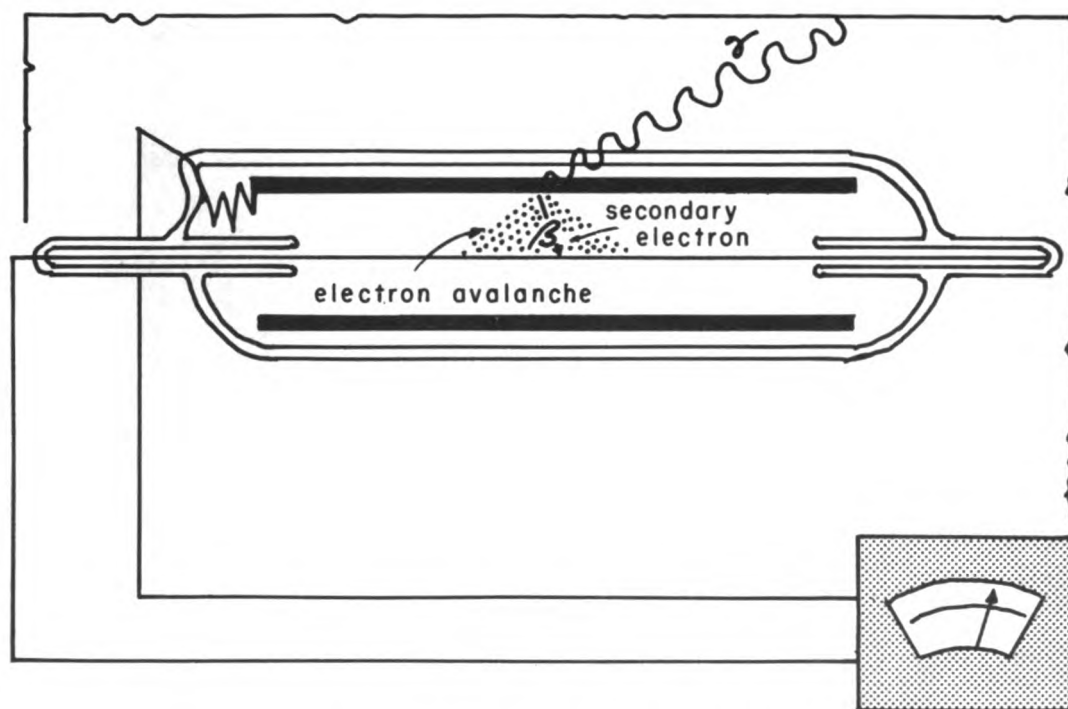
Just as the speedometer of a car indicates the speed and distance traveled, so radiacs measure either dose rate (r/hr) or dose (r). The exposure-monitoring radiacs generally read in r/hr, c/m (counts per minute), rad/hr, etc., that is, a quantity of absorbed radiation per unit time. The AN/PDR-27, AN/PDR-18, and AN/PDR-39 are examples of EXPOSURE-RATE radiacs. The integrating radiacs read in r or mr. The film badge and pocket ionization chambers are examples of EXPOSURE-integrating devices.



RADIATION VS CONTAMINATION

Another important distinction is between the radiation field (exposure rate) and contamination. **CONTAMINATION** is the unwanted radioactive material which is detected by its **RADIATION**. A person standing in a radioactive fallout field is being exposed to the radiation. A contaminated person in such a field is being exposed to both (a) the radiation field and (b) the radiation from the contamination on his body. When the contaminated person leaves the radiation field, the exposure from the radiation field ceases, but the radioactive material on his body will continue to irradiate him until it is removed. Furthermore, it is always possible that contamination will get into the body where it can irradiate the internal body organs.

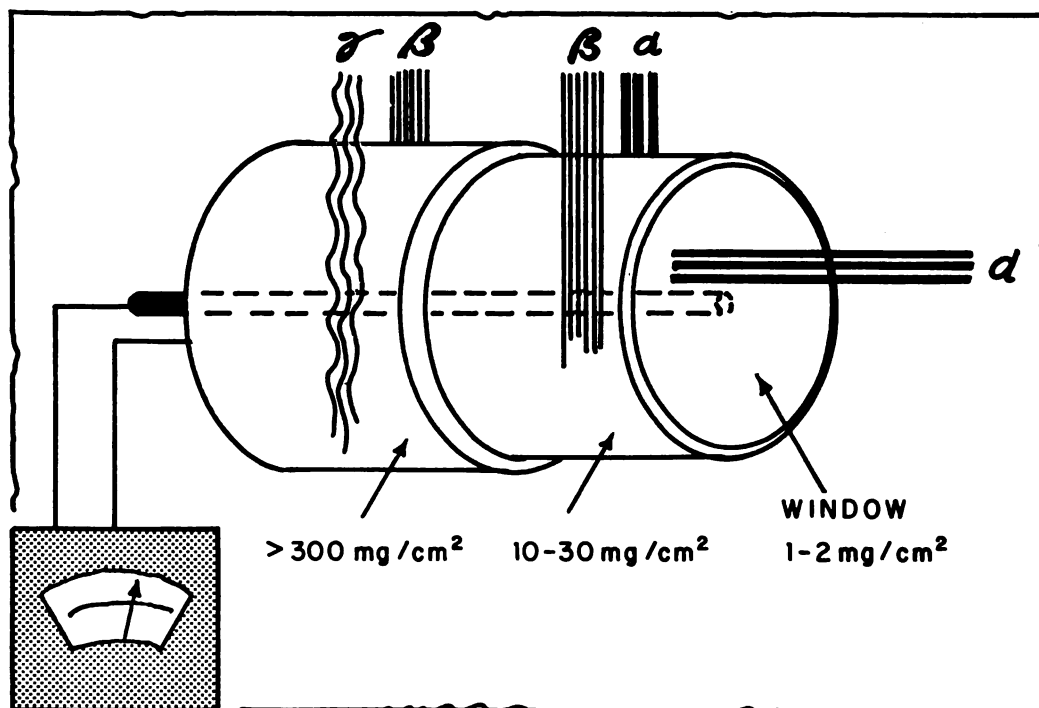
RADIATION MONITORING INSTRUMENTS



GEIGER-MUELLER TUBE

Ionizing radiation cannot be detected with the five senses. Man cannot hear, taste, or smell it and can only see and feel it if in very large amounts. We have to use physical and chemical devices to detect and measure it. Common radiacs measure the ionization produced by radiation. The above figure illustrates the ionization that triggers a geiger counter. The negative electrons are attracted to the positively charged wire and strip off other electrons from nearby atoms creating an avalanche of electrons rushing to the wire.

Through the process of ionization, the radiations transfer energy to the material through which they pass. The more rapidly the energy is given up, the sooner the transfer is completed and the less the penetrating power of the radiation. The density of ions in the narrow track left behind by the passage of the ionizing particle is called the "specific ionization." It is usually given in terms of ion pairs per micron of path.



IONIZATION CHAMBER

In the geiger counter, every count means one particle, whether it produces one pair of ions or 10,000. In the IONIZATION CHAMBER, the charge on the ions is collected so that a particle counts for more if it makes more ions. This is a good idea because the biological injury depends less on the number of particles and more on the number of ions they produce.

The collected ions produce a minute electrical current, which may be detected directly by a sensitive electrometer or may be amplified to give a meter reading. This current is a measure of the radiation.

When we wish to measure the gamma rays without the beta particles, we push the beta shield (one or two millimeters thick) over the ionization chamber. When we wish to measure beta particles, we pull the shield back. Of course the gammas get measured too. Alpha particles cannot get through even the wall of the chamber unless we have a special thin window (only a few milligrams per cm^2). The usual alpha window material is nylon or mylar, 0.001 inch thick or less. These are very easily ruptured and most radiacs are not provided with them. Radiacs with thick walls to make them sturdy can only be used for gammas. When they have walls thin enough for betas they must be used with care so as not to break the window. If the radiation detection element is damaged, the radiac can no longer be used.

RADIACS-TOOLS OF THE MONITOR

Every radiological monitor must know his instruments and be able to use them. A basic understanding of radiac instrumentation will allow the monitor to operate any standard radiac. Appendix B of this Volume gives detailed information on how to operate radiacs. Volume III, Chapter 3, gives additional information on the principles and theory of radiac design.

All rate-measuring radiacs (ratemeters) have the following common features:

ON and OFF switch

RANGE SELECTOR (the exposure rate of the radiation measured)

ZERO SET and/or CALIBRATE (controls to set up and check the operation of the radiac)

METER INDICATION (meter scale to give the intensity of radiation measured; many have earphones in addition)

BOX or HOUSING AROUND the TUBE or CHAMBER (with the necessary window and sometimes alpha and beta shields).

RATEMETERS measure the degree of radiation hazard - that is, the amount of threatening radiation that is present. Their purpose is to tell how much radiation a person might get. On Page 48 we talk about **DOSIMETERS** whose purpose is to indicate the accumulation of radiation dose.

REMEMBER - THE RADIACS CAN ONLY MEASURE THE PHYSICAL CAPABILITY OF RADIATION. THE MONITOR MUST TRANSLATE THIS INTO TERMS OF DANGER TO HEALTH.

DOSE RATE

AN/PDR-18 RADIAC SERIES

Just for gammas - high-exposure rate



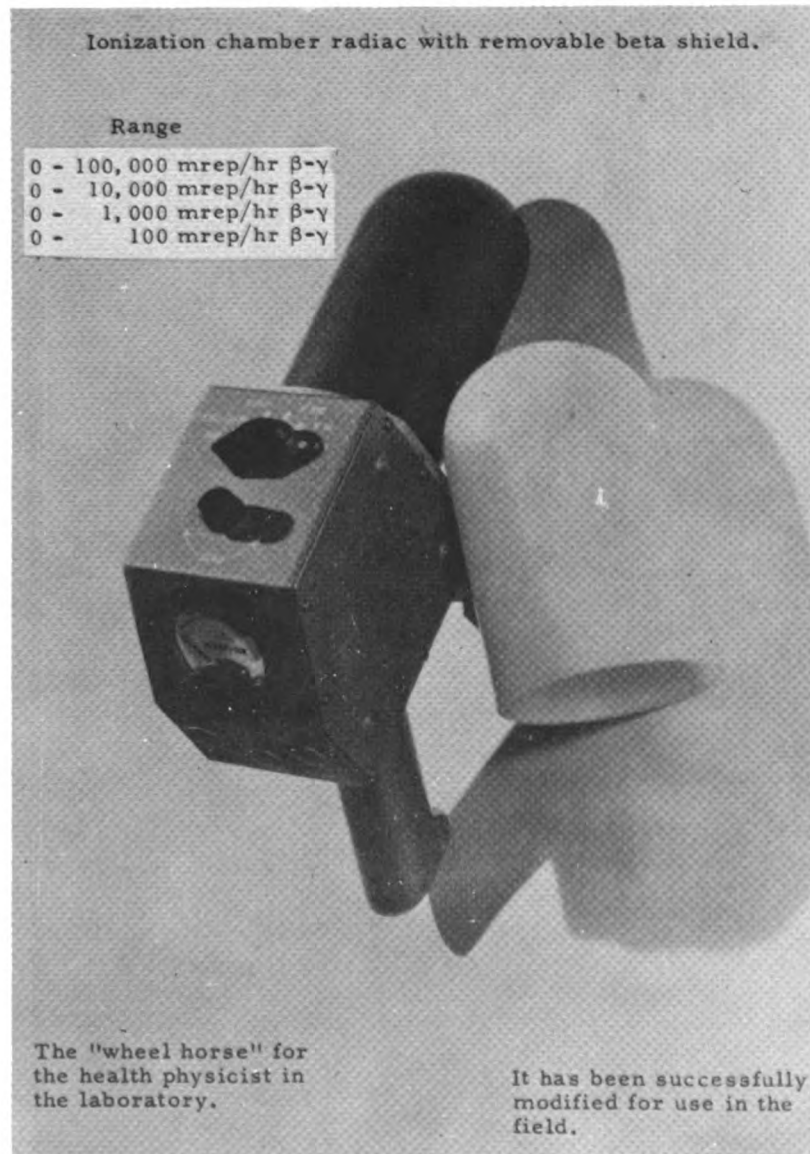
A gamma-detecting instrument with a crystal that gives flashes of light when radiation goes through it. A photomultiplier tube detects the flashes.

AN/PDR-39 (T1B) RADIAC

Just for gamma rays

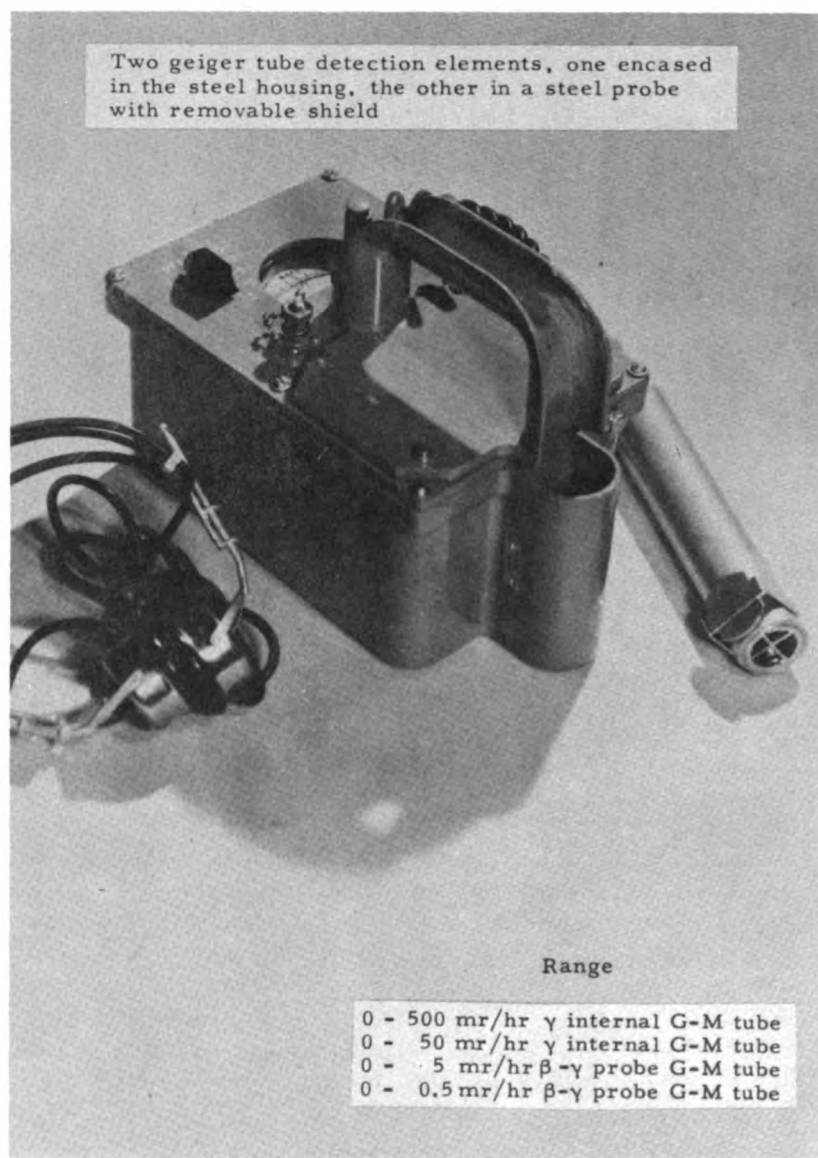


"CUTIE PIE" Model CP-3DM Beta-Gamma Survey Meter



AN/PDR-27 RADIAC SERIES

Called beta-gamma, although the beta range is low



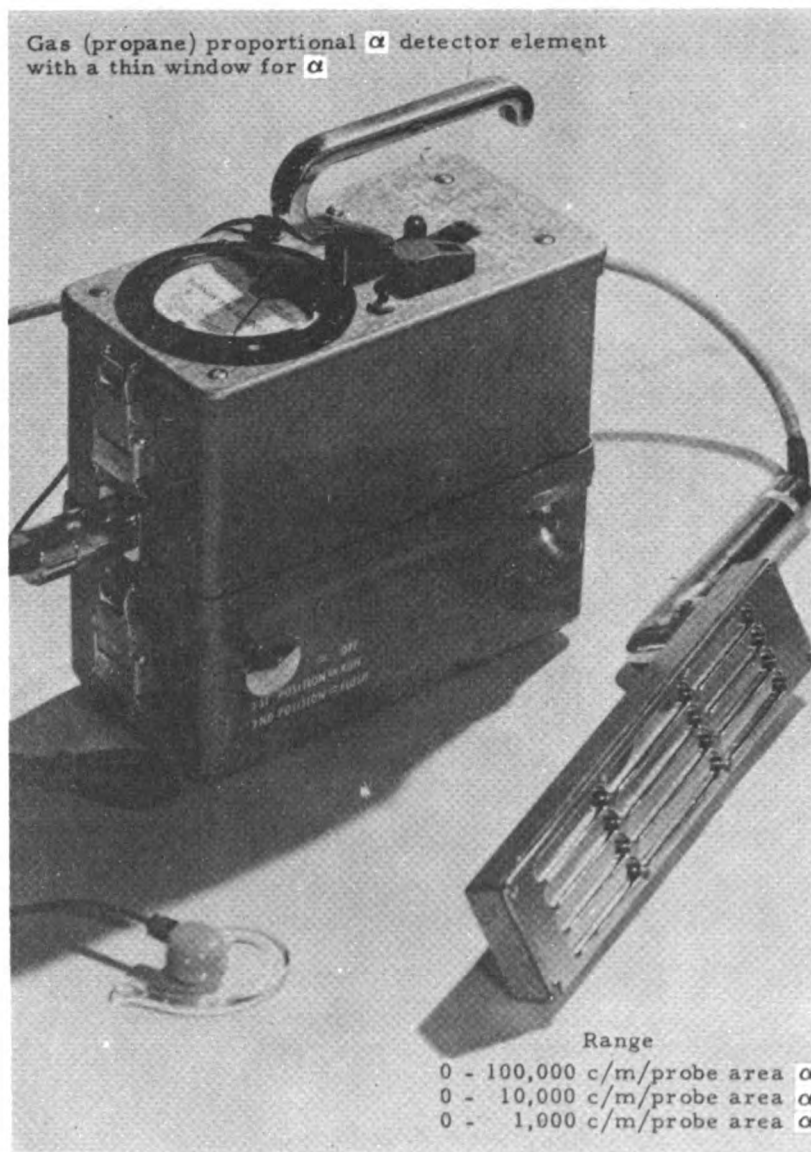
EBERLINE Model E-112B Beta-Gamma Survey Meter

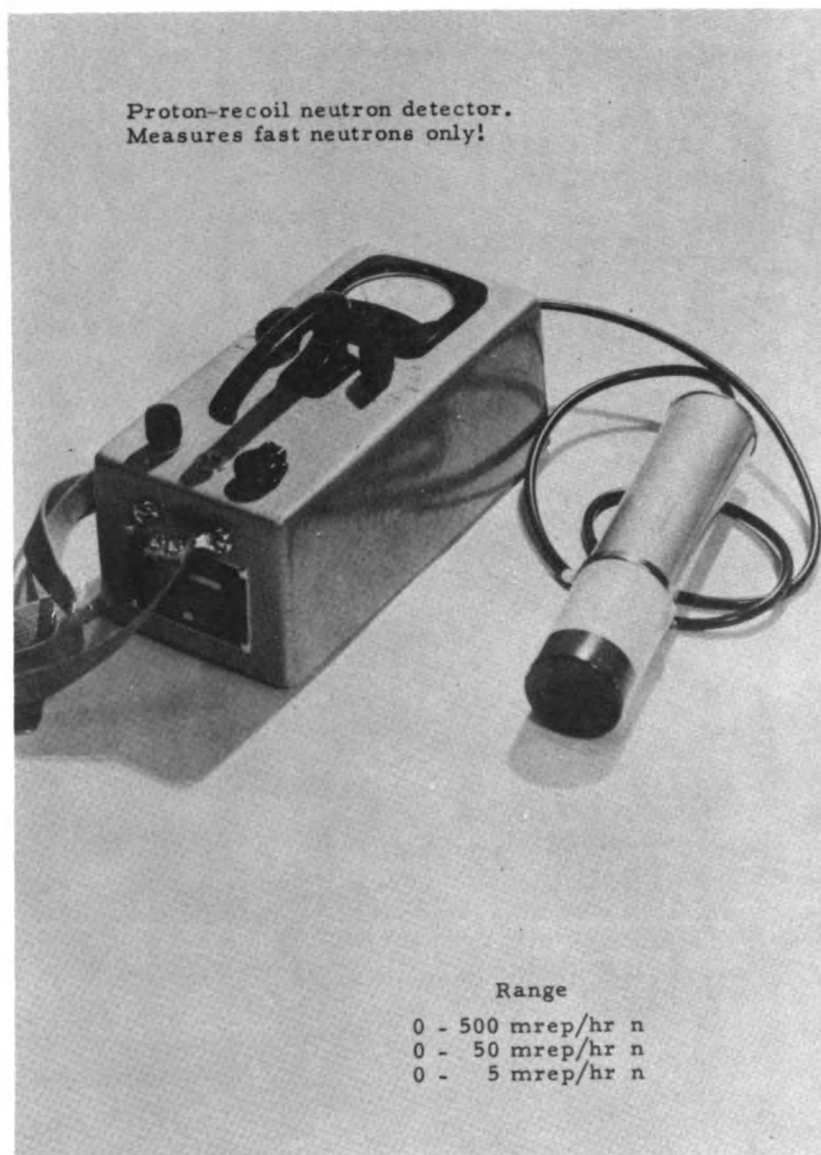


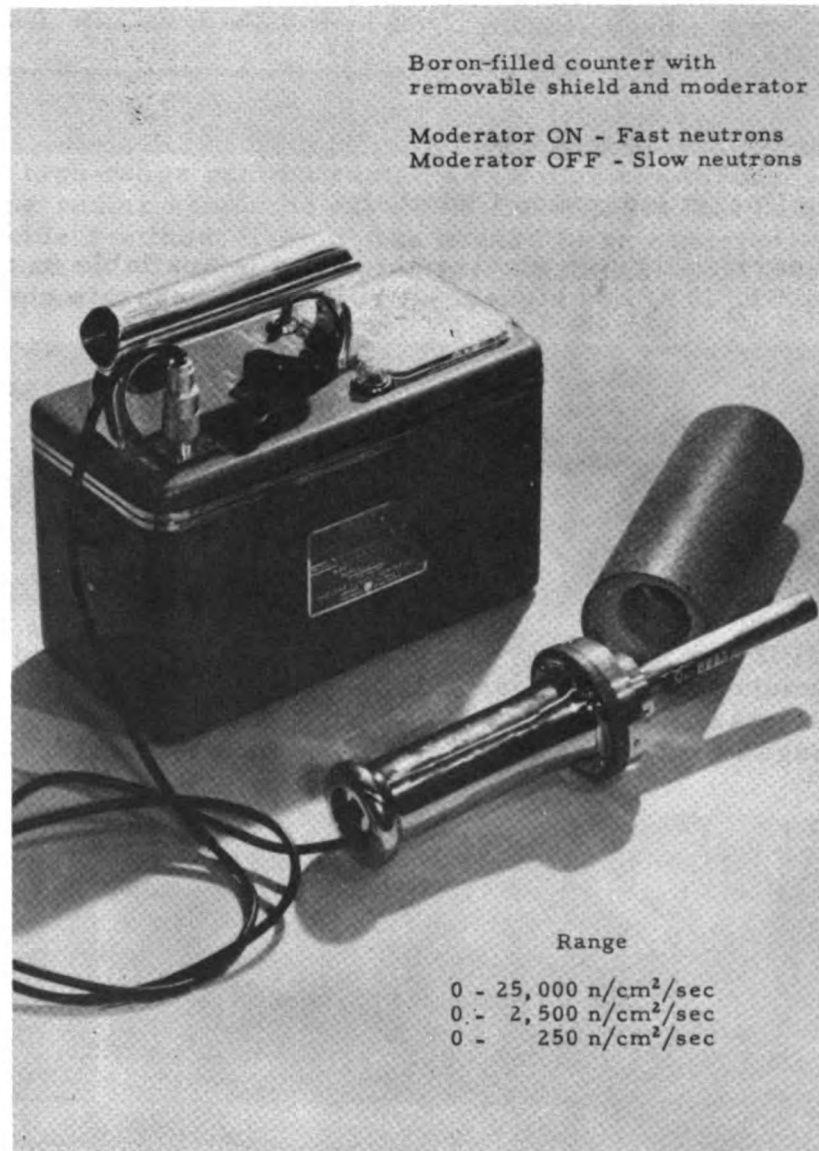
"JUNO" Model 3 Alpha-Beta-Gamma Survey Meter



AN/PDR-54 (EBERLINE PAC-3G) Alpha Contamination Meter

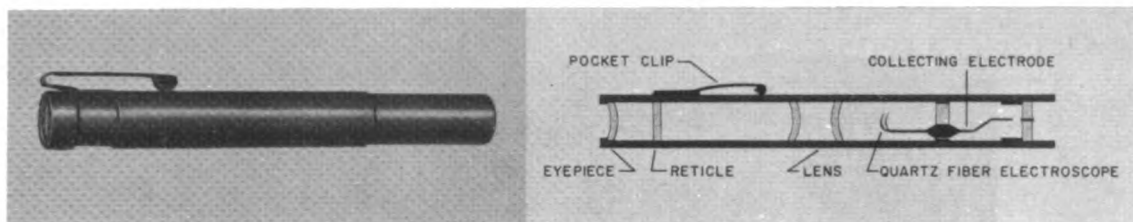






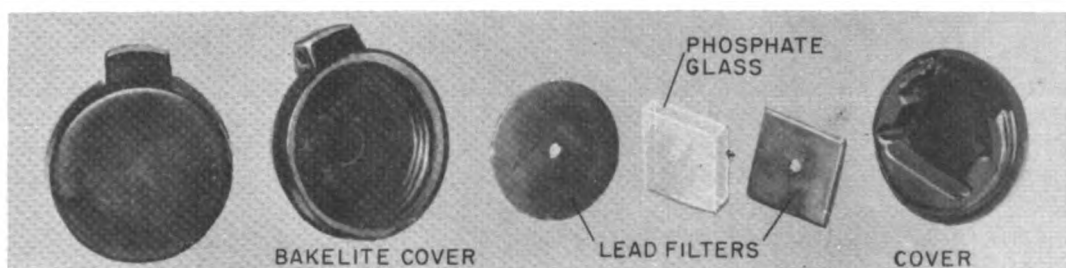
FOR PERSONNEL DOSIMETRY

The following pictures are examples of devices to measure integrated EXPOSURE.

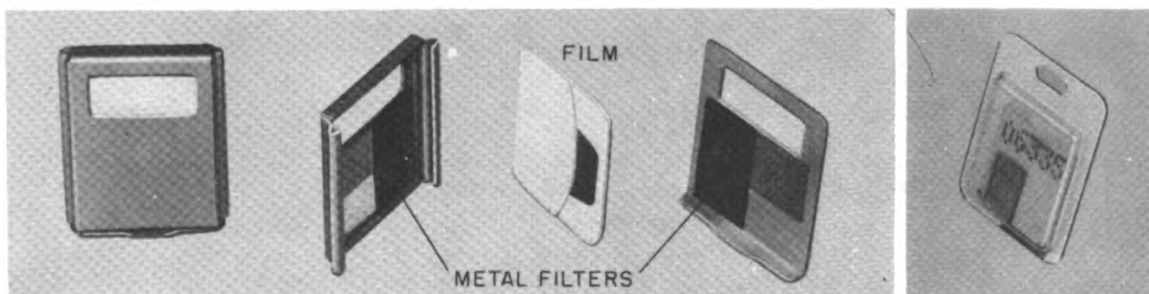


Self-Reading Pocket Ionization Chamber

This device carries its own electrometer and is available in ranges of 200 mr, 1 r, 5 r, 10 r, and higher. It requires a separate charging unit.



The DT-60/PD is a "casualty" personnel dosimeter designed to measure an accumulated gamma dose (25 r up to 600 r). The moisture-proof bakelite case holds the radiation-sensitive phosphate glass. The induced change in fluorescence is measured in the CP-95/PD reader.



Film Badges for Laboratory and Field

The detection element is photographic film. Metal or plastic filters covering part of the film permit estimation of the quality of the radiation so that the absorbed dose can be inferred from the measured exposure. Some use several films of different speeds to increase the range.

A MONITOR MUST KNOW HOW TO CHOOSE THE PROPER RADIAC FOR MONITORING SEVERAL TYPES OF RADIATION. He may have to take more than one instrument to cover the range of hazard that he expects to encounter. It will be assumed that the monitor will always know something about the radiation problem beforehand. For example, in a field operation the radioactive materials of interest will probably be fission products which emit beta particles and gamma rays. Therefore, one would take a gamma radiac and also a beta radiac. A gamma radiac is used first because the primary radiological hazard is caused by the penetrating gamma radiation. Gamma radiation irradiates the whole body. Beta radiation irradiates only the body surface.

When in doubt, a high-range gamma radiac and a medium-through-low-range beta-gamma radiac should be carried. But if there had been a nuclear bomb accident without fission, the hazard to be expected would be alpha contamination. The problem is utterly different and instruments and techniques must be adapted to it.

The following rules apply:

- 1 Choose the radiac that will measure the type or types of radiation of interest.
- 2 Make sure these radiacs will cover the range expected. Take two or more radiacs if necessary. (Select the most sensitive range that does not send the needle off scale.)
- 3 Don't forget to check the radiac to see that it is working right before leaving the radiac-issue center. If you are going far, take a standby instrument.
- 4 Handle radiacs with care - don't let careless people carry yours.

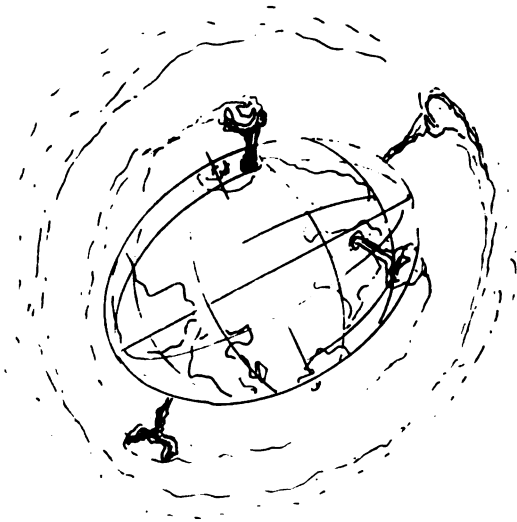
A practiced monitor will do these things instinctively every time he picks up a radiac.

A MONITOR IS NOT MUCH GOOD WITHOUT HIS RADIAC (a hound without his nose).

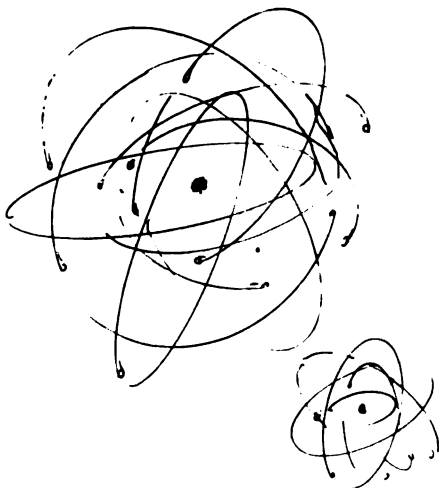
SUMMARY

Radiological Safety means avoiding exposure to external radiation and intake of radioactive material. In the language of the monitor, rad-safe means the ideals and techniques of getting the mission accomplished with the least possible irradiation of personnel. Knowledge of the hazard, familiarity with techniques of control, and resourcefulness in operation make for minimum necessary interference by the radiation.

RAD-SAFE IS THE MEANS TO THE END



In this Chapter we have set forth some of the causes of the increasing amount of ionizing radiations, reviewed the sources of these radiations and given methods of detection and control.

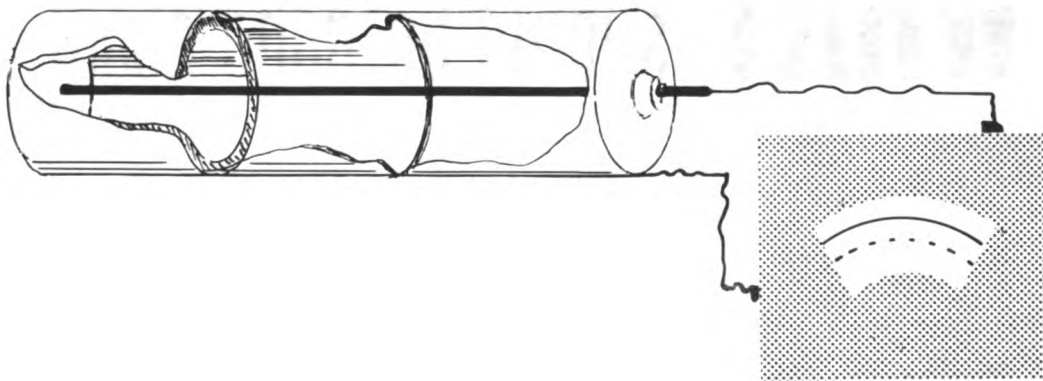


We have presented the accepted ideas about atomic structure and about radiations. All this information is basic to an understanding of the important field of radiological safety. We have given the limits of dose and exposure that are considered acceptable when people have to work where there is radiation.



Basic units roentgen, rad, and rem have been discussed. The effects on man have been indicated for various doses of radiation measured in these units.

In Chapter 1, radiacs have been pictured, and their functions and limitations described. Radiological safety requires that workers know the instruments and choose the right instrument for the job.



Pictures have been shown of some cases of exposure to large amounts of radiation. Since smaller amounts also do harm in proportion, THESE EXAMPLES EMPHASIZE THE NECESSITY OF ADEQUATE TRAINING IN RADIOLOGICAL SAFETY.

WHERE is the problem ?

WHAT should be done about it ?

CHAPTER

2

RADIOLOGICAL SAFETY

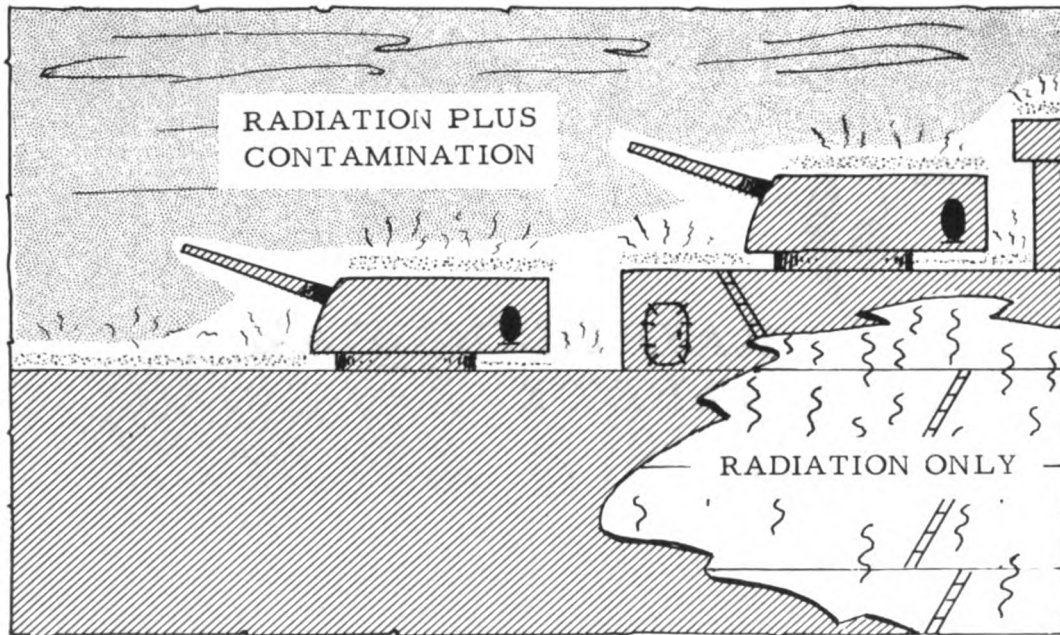
RADIATION HYGIENE is that branch of preventive medicine that concerns the preservation of health in the midst of ionizing radiation. **HEALTH PHYSICS** embodies those portions of physical science applicable to radiation hygiene. It provides: (a) understanding the problems associated with the use of radioactive materials and radiation sources; (b) understanding the use of equipment and facilities to minimize contact with radioactive materials and ionizing radiations. **RADIOLOGICAL SAFETY** is the discipline required for the control of radiation and contamination, thereby assuring compliance with the established MPE's and MPC's.

Radiation Hygiene - health in spite of radiation

Health Physicist - the watch dog

Radiological safety demands a complete evaluation of every radiological situation (**ASSESSMENT**) so that unauthorized personnel can be kept out of areas of hazard (**DELINEATION**) and so that radioactive material can be prevented from contaminating personnel or the environment (**CONTROL**).

RADIATION VS CONTAMINATION



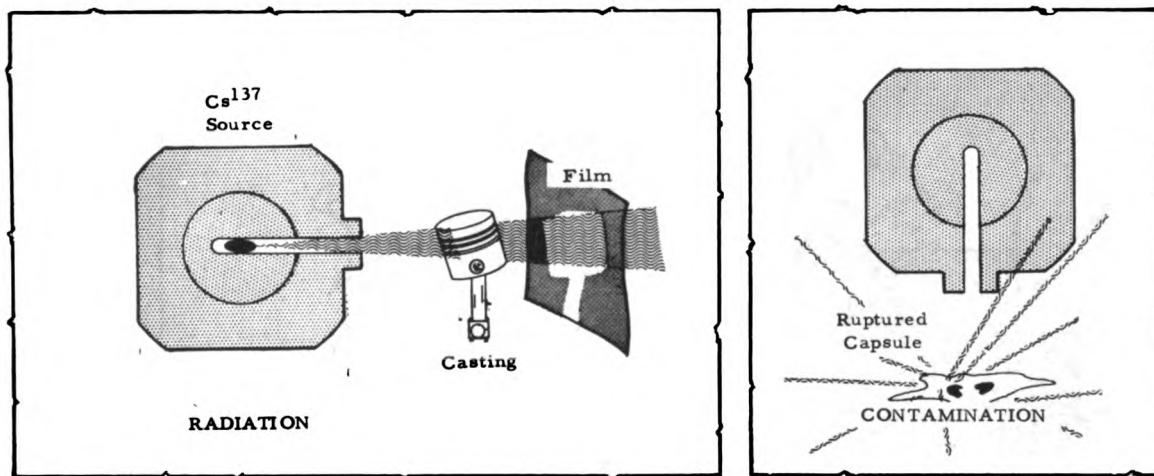
Assessment, delineation, and control of radiation and contamination are the basic functions of Radiological Safety. Radiological safety procedures will depend upon the radiation intensities and contamination potentials of the sources of ionizing radiations.

RADIATION - - ionizing radiations emitted by machines and radioactive materials. Radioactive materials are radioactive isotopes emitting one or more types of ionizing radiations (alpha and beta particles and gamma rays).

CONTAMINATION - - radioactive materials in an undesired location. Radioactive contamination is radioactive dirt that may be harmful to personnel or may jeopardize experimental measurements or industrial processes.

CONTAMINATION SOURCE - - radioactive material in a condition capable of being spread by movement of personnel, equipment, and effects of the weather.

For example, a cesium-137 (Cs^{137}) gamma source is used for radiography. The radioactive material, Cs^{137} , is sealed inside a stainless steel capsule. The gamma rays penetrate the steel capsule and are the radiations used to make radiographs of thick coatings (nondestructive testing). This is a RADIATION SOURCE. Dosage received from a radiation source is controlled by the proper use of time, distance, and shielding.



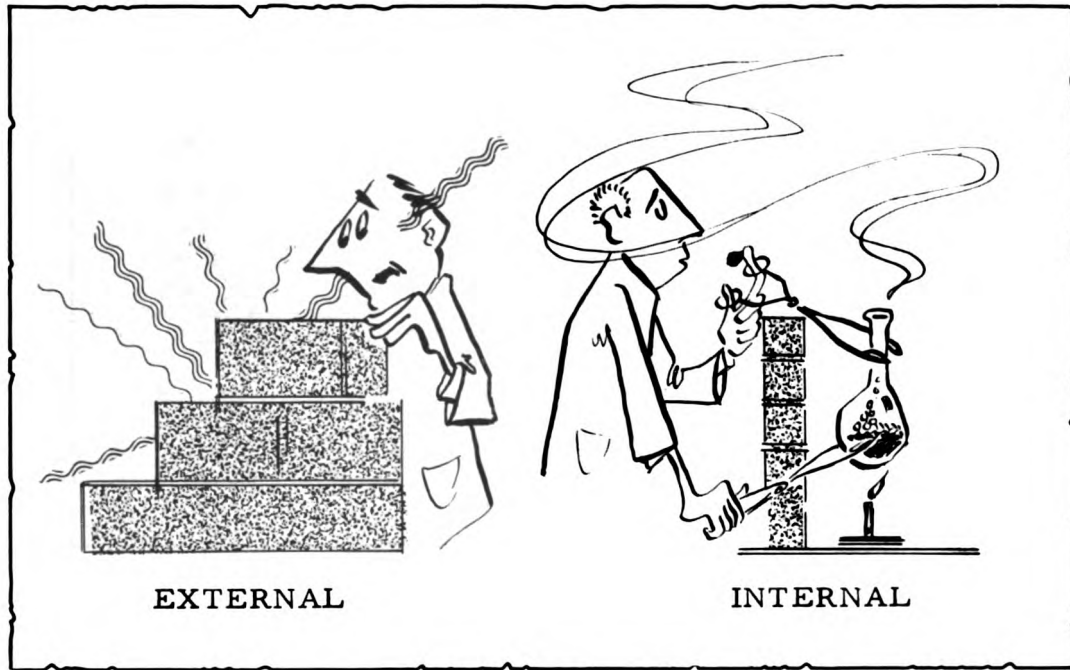
As long as the Cs^{137} is sealed in the capsule, there is no radioactive contamination. If the capsule were broken and the Cs^{137} spilled, this would then be a CONTAMINATION SOURCE. Dosage received from a contamination source is also controlled by the proper use of time, distance, and shielding. In addition, decontamination plus other safeguards must be employed to prevent the ingestion, inhalation, and absorption of radioactive material into the body.

A CONTAMINATED OBJECT IS NOT ITSELF RADIOACTIVE. It may be cleaned (decontaminated) by removing the radioactive material.

An object may be made radioactive only BY SUFFICIENT EXPOSURE TO NEUTRON RADIATION. No other type of radiation -- alpha, beta, or gamma -- can normally induce radioactivity into a nonradioactive material. Since neutrons are present only in nuclear reactors, accelerators, specially prepared sources, and for short periods in nuclear explosions, the possibility of making human beings radioactive, for all practical purposes, does not exist.

RADIATION DOSAGE CONTROL

Exposure to ionizing radiations may be divided into two categories: (1) External Radiation and (2) Internal Contamination. EXTERNAL RADIATION comes from a radiation source outside the body. INTERNAL CONTAMINATION means radioactive material inside the body.



The radiation dosage received from ionizing radiation depends upon three factors:

- ① Type of radiation
- ② Amount of radiation
- ③ Total exposure time.

Therefore, if the source of the radiation is outside the body, the exposure time may be controlled simply by leaving the radiation area. If the radioactive material enters the body, the exposure becomes continuous and lasts until the radioactive material has decayed away or is biologically eliminated. Thus, two general control problems are to be considered: external radiation dosage control and internal contamination control.

EXTERNAL RADIATION DOSAGE CONTROL

External irradiation may be controlled by one or a combination of the following:

- ① TIME exposed to the radiation
- ② DISTANCE from the radiation source
- ③ SHIELDING between personnel and radiation source
- ④ RADIOACTIVE DECAY.



For example, suppose it is necessary to perform a certain job in an area 1 foot from a point source of radiation. The potential dose rate from this source has been determined by a radiac measurement to be 100 rad/hr at 1 foot (γ).

The dose, D , developed in a time, T , in a radiation field of potential dose rate, I , is given by the equation:

$$D = I \times T$$

TIME AND DOSE RATE MUST BE MEASURED IN THE SAME UNITS OF TIME.

Example: A potential dose rate of 100 rad/hr for an exposure time of 10 minutes would give:

$$D = 100 \frac{\text{rad}}{\text{hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times 10 \text{ min} = 16.6 = 17 \text{ rad}$$

(Note: Minutes must be converted to hours)

Appendix C presents a basic review of mathematics and Appendix D lists useful conversion factors.

The following table illustrates the radiation dose that would result for various working times (stay-times) when the potential dose rate is 100 rad/hr.

STAY-TIME	TOTAL DOSE
1 minute (1/60 of an hr)	1.7 rad
10 minutes (1/6 of an hr)	17 rad
1 hour	100 rad
8 hours	800 rad

If a job requires 8 man-hours working time in the above 100 rad/hr field, allowing an MPE of 5 rad per man, it would be impractical to attempt the operation by controlling only the time of exposure since each man would be limited to slightly less than 3 minutes of working time.



DISTANCE

The dose rate can be lessened by increasing the distance between the radiation source and working personnel. The radiation intensity varies inversely as the square of the distance from a point source. If I_0 is the radiation intensity at unit distance, then the radiation intensity, I , at any distance, r , is given by

$$I = I_0 \times \left(\frac{1}{r}\right)^2$$

If unit distance for I_0 is one foot, then r must be given in feet.

As long as both distances are measured in the same units, the radiation intensity, I_b , at a distance, r_b , is related to the radiation intensity, I_a , at any other distance, r_a , by

$$\frac{I_b}{I_a} = \left(\frac{r_a}{r_b}\right)^2$$

Remember that the intensity is always less at the greater distance.

Example: If the potential dose rate at a distance of 1 foot from the source is 100 rad/hr, what will be the rate at 8 foot distance?

$$I_a = 100 \text{ rad/hr}$$

$$I_b = ?$$

$$r_a = 1 \text{ ft}$$

$$r_b = 8 \text{ ft}$$

Substitute these values into the equation and solve for I_b .

$$\frac{I_b}{100} = \left(\frac{1}{8}\right)^2$$

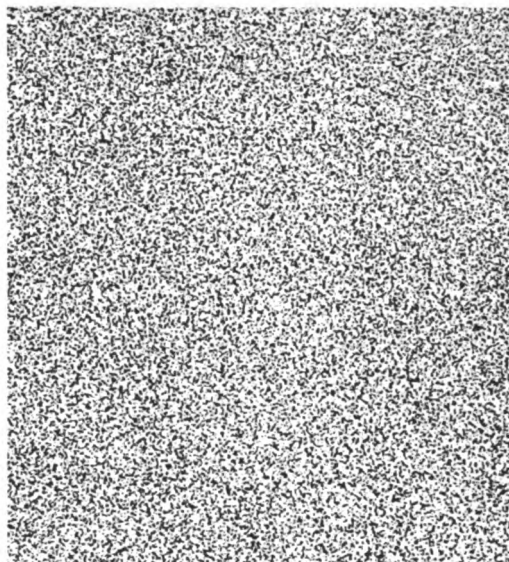
$$I_b = \frac{100}{64} = 1.6 \text{ rad/hr}$$

The following table illustrates the dose that would be received for various working times (stay-times) from a source whose dose rate is 100 rad per hour at 1 foot, as before, but now increasing the working distance to 8 feet:

STAY-TIME	TOTAL DOSE
1 minute	0.027 rad (27 mrad)
10 minutes	0.27 rad
1 hour	1.6 rad
8 hours	13.0 rad

With the same MPE of 5 rad per man, one man may now work on the job for 3 hours by moving back 8 feet from the radiation source. The stay-time is thus increased from 3 minutes to 180 minutes.

SHIELDING



The radiation intensity of a source can be reduced by placing material (SHIELDING) around the source to absorb some of the radiation. The thickness of the shielding material required depends on the amount and quality of the radiation (for the same degree of protection).

If we are dealing with gamma rays of 1 Mev energy, only 10% will get through a 2 inch steel shield. The following table illustrates what would happen in the previous problem with and without the steel shield.

STAY-TIME	TOTAL DOSE			
	1 ft distance		8 ft distance	
	No Shield	2 in. Steel Shield	No Shield	2 in. Steel Shield
1 minute	1.7 rad	0.17 rad	27 mrad	2.7 mrad
10 minutes	17 rad	1.7 rad	270 mrad	27 mrad
1 hour	100 rad	10 rad	1.6 rad	0.16 rad
8 hours	800 rad	80 rad	13 rad	1.3 rad

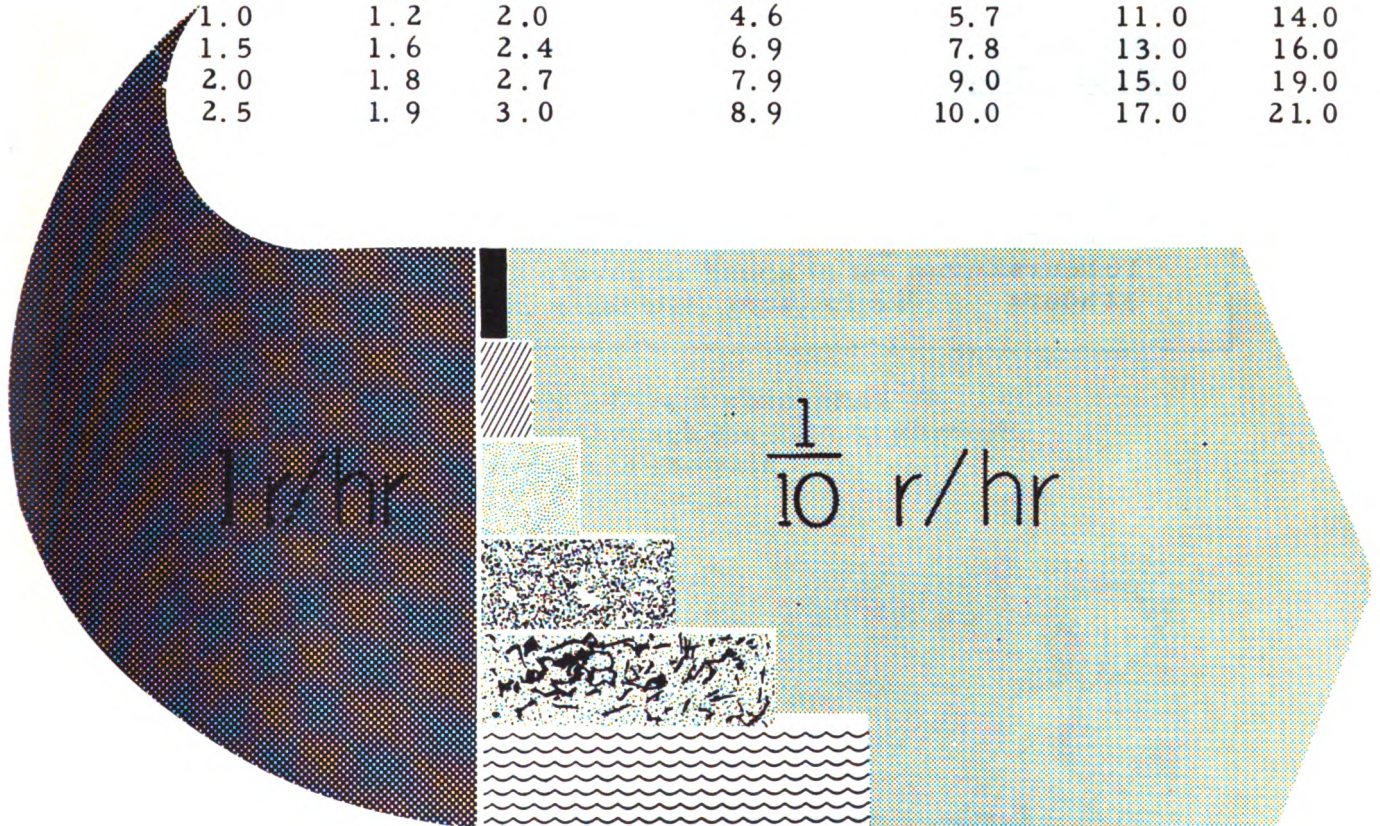
With the shielding, and working at 8 ft distance, the job may now be performed by one man who will receive 1.3 rad.

TENTH-VALUE LAYERS FOR GAMMA RADIATION

The TENTH-VALUE LAYER is defined as that amount of shielding material that will reduce the radiation dose rate to one-tenth of the original amount. Tenth-value layers for gamma radiation shielding for various energies are given in the following table. (Other energies and materials are presented in Appendix E).

TENTH-VALUE LAYERS FOR GAMMA RADIATION
(Thickness of Material in Inches)

Gamma Energy (Mev)	Lead	Steel	Aluminum	Concrete	Earth	Water
0.2	0.09	0.79	2.7	2.7	5.5	6.7
0.5	0.54	1.4	3.9	4.2	7.8	9.4
1.0	1.2	2.0	4.6	5.7	11.0	14.0
1.5	1.6	2.4	6.9	7.8	13.0	16.0
2.0	1.8	2.7	7.9	9.0	15.0	19.0
2.5	1.9	3.0	8.9	10.0	17.0	21.0

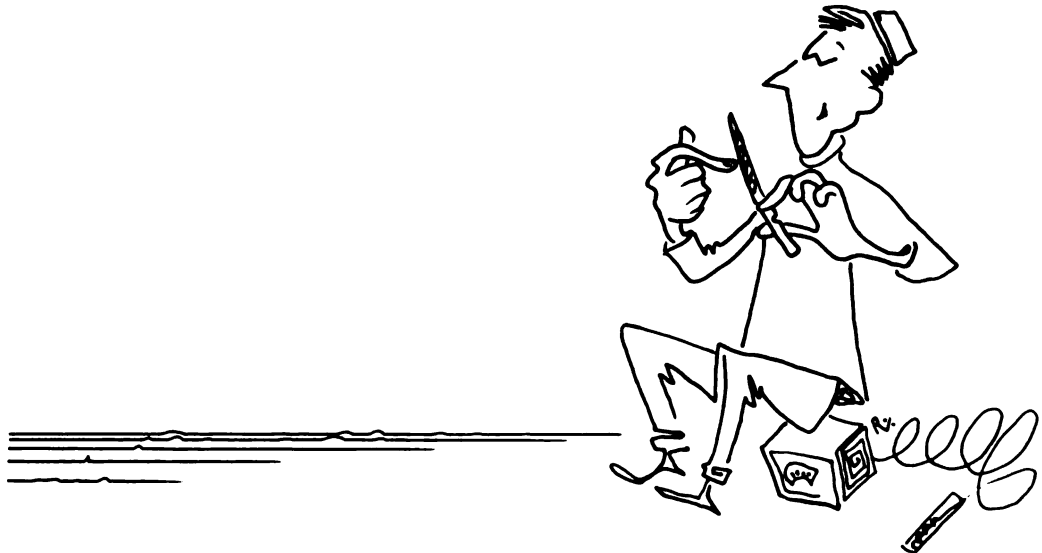


DECAY

The fourth method of controlling dosage consists of waiting for the reduction of radiation intensity through the decay of the radioactive material. The decay method of dosage control can generally be used in the case of early-time fission products and short-lived radioisotopes. (Chapter 2 of Volume III presents additional information on radioactive decay.)

For example, consider the situation after a nuclear explosion. Some operation has to be done in the contaminated area. At a time 1 hour after the detonation, the dose rate measured in the work area by a radiac instrument is 100 r/hr. Roughly speaking, **THE DOSE RATE FROM FISSION PRODUCTS IS CUT IN TWO FOR EVERY DOUBLING OF THE TIME SINCE THE DETONATION** (first Rule of Thumb, Page 128). The following table shows how much the dose rate falls off the longer you wait.

<u>TIME AFTER DETONATION</u>	<u>RADIATION DOSE RATE IN WORK AREA</u>
1 hour	100 r/hr
2 hours	50 r/hr
4 hours	25 r/hr
8 hours	13 r/hr
16 hours	6.5 r/hr
32 hours	3.2 r/hr



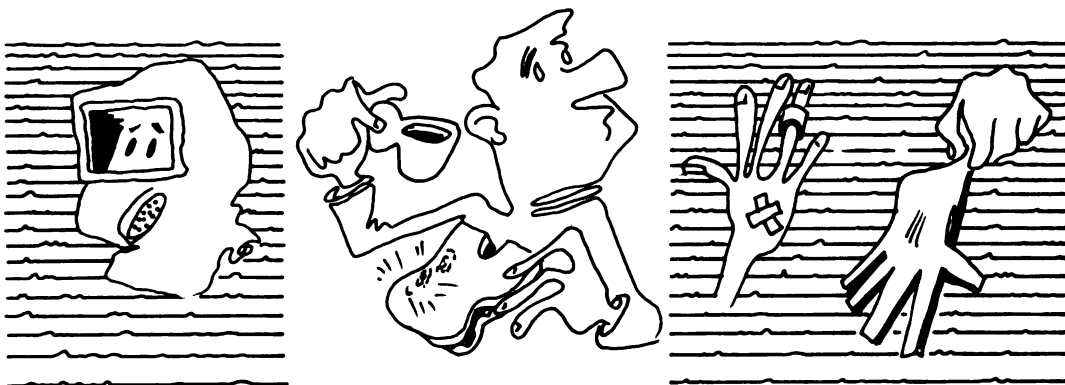
INTERNAL CONTAMINATION CONTROL

Exposure to external ionizing radiation ceases when one leaves the radiation area. There is, however, the problem of exposure caused by contact with radioactive materials. In almost every contact with loose radioactive materials, some is carried away as "contamination."

For this reason, IT IS IMPORTANT THAT PERSONNEL WORKING IN THE PRESENCE OF LOOSE RADIOACTIVE MATERIAL AVOID TOUCHING IT WITH THEIR BARE HANDS AND WEAR PROTECTIVE CLOTHING. Such radioactive contamination, when transferred to skin or clothing, will provide a source of radiation until removed. Failure to remove skin contamination has often resulted in radiation burns. In general, the use of barriers such as gloves and special protective clothing will prevent contamination of skin and personal clothing and will also provide shielding from radiations of low penetrating power.

Radioactive materials may enter the body through

- 1 INHALATION - Breathing radioactive dust
- 2 INGESTION - Eating or drinking contaminated food and water or transferring contamination from gloves or hands to the mouth (or lipstick, cigarette, pipe, cigar).
- 3 ABSORPTION - Direct absorption of contamination through the skin or through cuts and breaks in the skin.

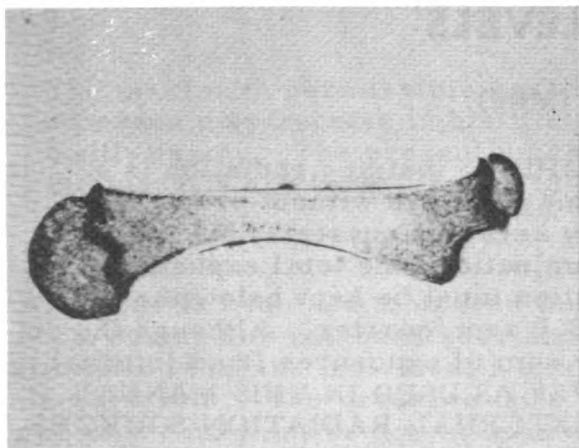


When a radioactive element is taken into the body, it is deposited in various organs. The chemical and physical characteristics of the radioactive isotope determine the organ in which it will be deposited and later its excretion rate. A radioactive isotope will follow the same metabolic processes as a stable isotope of the same element. If the radioelement has no counterpart which is normally found in the body, it will follow the pattern of another element with similar chemical properties. For example, only traces of barium and strontium are found normally in the body, but they have properties similar to calcium; thus if any get in they will be distributed like calcium in the body's tissues, mostly, of course, in the bone.

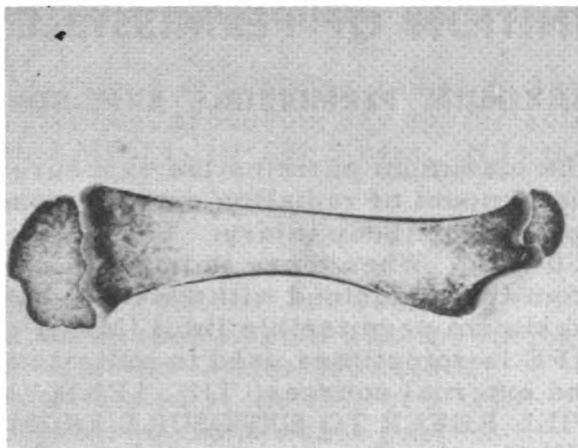
Once radioactive material has entered the body, it does continuous damage until it is biologically eliminated or until it has decayed to a stable element. The time required for the radioactive element to be reduced by one-half through the combined action of elimination and decay is called Effective Half-life. At the present time there is little that can be done to accelerate the elimination. Therefore, the control of internal contamination is prevention of inhalation, ingestion, or absorption of radioactive materials.

Internal contamination is usually more serious than external radiation because:

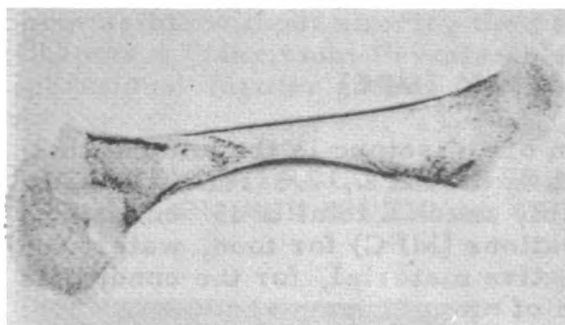
- ① You carry the radiating source around with you. The rate of elimination from the body is very slow for some radioisotopes. Appendix A lists the MPC's, physical, biological and effective half-life, body burden and organ of reference for various radioactive isotopes.
- ② Radioactive materials inside the body permit alpha and beta radiations to reach radiosensitive tissue and to dissipate all their energy in a small volume thus irradiating heavily the cells that are close to them.
- ③ Especially for alphas and betas, it is next to impossible to assess the degree of internal contamination accurately; even for gammas it is difficult to measure the amount and distribution inside the body.



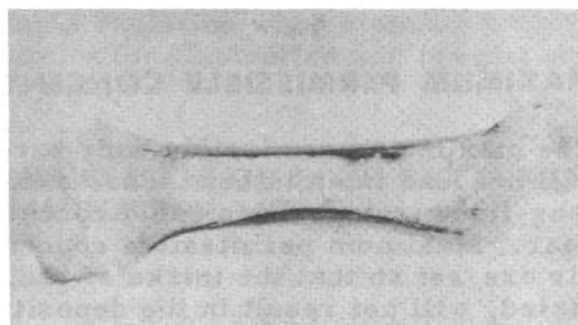
24 HR AFTER INJECTION



10 DAYS AFTER INJECTION



30 DAYS AFTER INJECTION



60 DAYS AFTER INJECTION

RADIOAUTOGRAPH OF THE FEMUR OF A YOUNG PIG INJECTED INTRAVENOUSLY WITH Ca^{45}

If a radioisotope has become deposited in the body, the exposure from the deposited material is continuous and, in some cases, may last for a lifetime. Generally speaking, radiation effects from internal contamination are similar to whole-body radiation. However, certain radioactive isotopes are selectively taken up in individual organs and cause "partial-body irradiation." Such internal contamination may alter the function of the organ or destroy it. Above are shown autographs of radioactive material in a bone. The ionizing radiations darkened the photographic film showing the exact areas of deposition of the radioactive material. Clinical medicine takes advantage of such deposition for diagnostic purposes and, in a few instances, for treatment. Properly used, radioisotopes benefit man; improperly used, they are harmful.

DEFINITION OF PERMISSIBLE LEVELS

MAXIMUM PERMISSIBLE EXPOSURE (MPE)

The maximum permissible exposure (MPE) to ionizing radiation is that amount of radiation exposure one may receive without producing appreciable body injury. The presently accepted quarterly MPE is 3.0 rem. When there is internal contamination, the total exposure from this combined with external radiation must be kept below the maximum permissible limit (MPL) of 3.0 rem/quarter. Although the MPE is sometimes used to indicate the sum of exposures from internal and external sources, THE TERM "MPE" AS USED IN THIS MANUAL WILL REFER TO EXPOSURE FROM EXTERNAL RADIATION SOURCES ONLY.

MAXIMUM PERMISSIBLE CONCENTRATION (MPC)

The maximum permissible body burden of an isotope is the amount that will not lead to an internal dose exceeding the MPL, 0.3 rem/wk. For long-lived isotopes this could conceivably reach a total of 15 rem in a year. Maximum permissible concentrations (MPC) for food, water, and air are set so that the intake of radioactive material, for the conditions stated, will not result in the deposition of more than one body burden. The latest listings of maximum permissible body burden and MPC's are reproduced in Appendix A.

MAXIMUM PERMISSIBLE LIMIT (MPL)

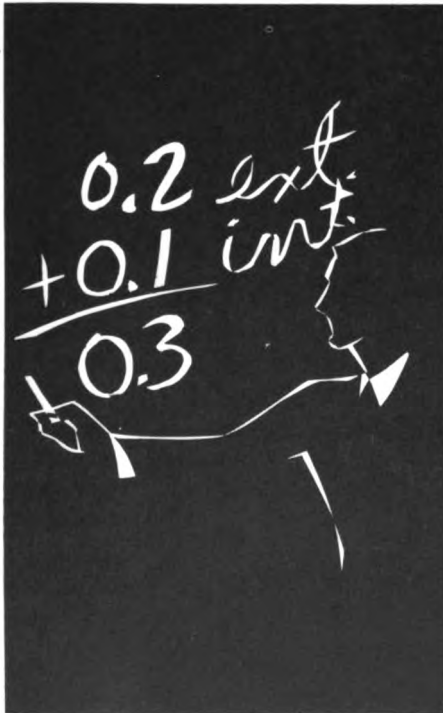
The maximum permissible limit (MPL) of ionizing radiation is the total dose from internal contamination and external radiation combined that will not result in a dose that will produce appreciable body injury. The presently accepted MPL is 3.0 rem/quarter. As used here, "appreciable bodily injury" means any injury or effect that the average person would become aware of or that a physician would regard as being perceptibly harmful to the health and well-being of the individual. THE TERM "MPL" WILL BE USED IN THIS MANUAL TO REFER TO THE MPE AND MPC COLLECTIVELY AND IS THE SUM OF THE EXPOSURE FROM EXTERNAL AND INTERNAL SOURCES. The limits on the dose rates and surface contamination levels necessary to assure compliance with the established total permissible dose are also called MPL's.

MAXIMUM PERMISSIBLE DOSE (MPD)

The maximum permissible dose is that dose of ionizing radiation that a person may receive in his lifetime without producing any appreciable bodily injury. The presently accepted MPD is $(N-18) \cdot 5$ rem. N is the individual's age (greater than 18).

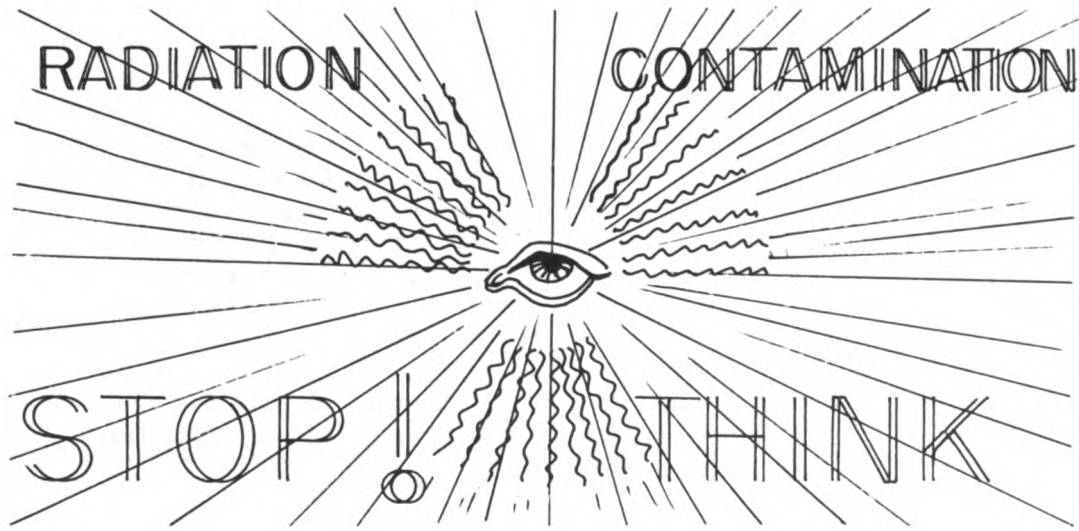
When one is required to exceed the quarterly MPL of 3.0 rem, the MPL during any calendar year should not exceed 12 rem with the further limitation that the individual's total lifetime MPD does not exceed $(N-18) \cdot 5$ rem. The "reserve dose" accumulated at the rate of 5 rem per year, may not be drawn upon except for persons whose past exposure is known to be negligible or has been measured and recorded. The National Committee on Radiation Protection (NCRP) states in NBS 69 that in emergency or accident situations, a dose of 25 rem is permissible without altering the person's radiation work status. (Chapter 4 "Maximum Permissible Limits for Controlled and Special Operations" further amplifies this subject.)

DOSAGE CONTROL REQUIRES A KNOWLEDGE OF BOTH EXTERNAL RADIATION AND INTERNAL CONTAMINATION.



The MPE's and MPC's are calculated to be the maximum safe working levels for continuous exposure day after day throughout the lifetime of the person exposed. Should a situation arise where personnel are exposed to more than this, the degree of biological damage will depend upon how much the MPE or MPC are exceeded. Additional information on the biological effects of radiation is presented in Chapter 1, Volume III.

RADIOLOGICAL SAFETY REQUIREMENTS



THE FUNDAMENTAL GOAL IN RADIOLOGICAL SAFETY IS TO MINIMIZE PERSONNEL EXPOSURE TO IONIZING RADIATIONS FROM EXTERNAL SOURCES AND TO MINIMIZE THE DEPOSITION OF RADIOACTIVE MATERIAL ON OR INSIDE THE BODY.

When one is working with radioactive materials and machines producing ionizing radiations, it is not always possible to keep external and internal radiation exposure to zero. Nevertheless, one should always plan a job for minimum exposure and in no case (barring accidents) should the dose exceed the MPL. Chapter 4 discusses the MPL's for controlled industrial operations and recommends MPL's for other radiological situations.

Working with radioactive materials is not mysterious. As in all other types of work, certain general safety precautions must be followed. Basic ground rules exist for working with ionizing radiations.

Rad-safe procedures are determined by the radiation field and the contamination potential. Work with radiation-producing machines and sealed sources requires external dosage control. Work with radioactive materials requires, in addition, the control of the chance of internal contamination.

**ALL WORK WITH RADIATION-PRODUCING MACHINES AND
SEALED RADIATION SOURCES REQUIRES:**

- 1** GENERAL GOOD HOUSEKEEPING. (A neat, clean work space encourages personnel to be careful in their work.)
- 2** MINIMIZING EXTERNAL RADIATION EXPOSURE through the control of occupancy and rotation of personnel, if necessary.
- 3** WEARING PERSONNEL DOSIMETERS. (Film badges should be used to measure the total body dose for extended periods of time, while pocket ionization chambers may be used to measure the daily body exposure or the accumulation from hour to hour.)
- 4** MEASURING THE RADIATION FIELD in order to establish dosage control procedures.
- 5** PLANNING ALL JOBS after a thorough study of the field and establishing standard operating procedures for repetitive jobs.
- 6** MARKING THE RADIATION AREA in order to delineate the danger zone to prevent entry of unauthorized personnel.

ALL WORK WITH RADIOACTIVE MATERIALS REQUIRES:

- 1 GENERAL GOOD HOUSE-KEEPING.**
- 2 MINIMIZING** both external radiation exposure and internal contamination.
- 3 WEARING PERSONNEL DOSIMETERS.**
- 4 PLANNING ALL JOBS.** Determine the properties of the radioactive materials and review the experimental procedures. Set up flow plan (stepwise experimental procedures) and conduct dry runs.
- 5 SETTING UP AEROSOL SAMPLING** to measure the airborne radioactive material. Radiacs and film badges will not measure the internal contamination potential.
- 6 MEASURING THE RADIATION INTENSITY AND DETERMINING WHETHER THE ACTIVITY IS FIXED OR LOOSE** in order to establish the necessary controls.
- 7 MARKING THE WORK AREA** to delineate the radiation-contamination zone.
- 8 ESTABLISHING CONTAMINATION CONTROL PROCEDURES.** (Use protective equipment, set up decontamination center, dispose of radioactive waste.)
- 9 NOT EATING, DRINKING, OR SMOKING** in work areas unless under controlled conditions. There is always danger of contamination and transfer of radioactive material into the body.



FACTORS FOR THE MONITOR

Every person working with ionizing radiations should be thoroughly familiar with rad-safe work procedures. These basic procedures should be "second nature" to "atomic workers." In addition, rad-safe personnel (the monitor and rad-safe supervisor) must assess every radiological situation by answering the following questions:

- ① What types of radiation are present?
- ② What are the dose rates of these radiations?
- ③ What are the relative effects of each type of radiation?
- ④ What are the stay-time limits in each area?
- ⑤ What is the contamination problem, the type of contamination, and the amount of removable contamination?
- ⑥ Will the removable contamination create an internal contamination problem?
- ⑦ Will the removable contamination create an industrial nuisance by jeopardizing low background areas and equipment?
- ⑧ Is there an airborne contamination problem?
- ⑨ What controls must be established to protect personnel?

The answers to these questions will determine the operating procedures and the equipment that must be employed to make the operation radiologically safe.

Certain operations are known to produce radiological problems. A number of these are listed below:

RADIOACTIVE AEROSOL PRODUCTION

- ① Cutting, burning, or welding contaminated metal.
- ② Sandblasting, wire brushing, and chipping contaminated surfaces.
- ③ Heating and boiling radioactive liquids.
- ④ Spray from decontamination operations.

CONTAMINATION SPREADING

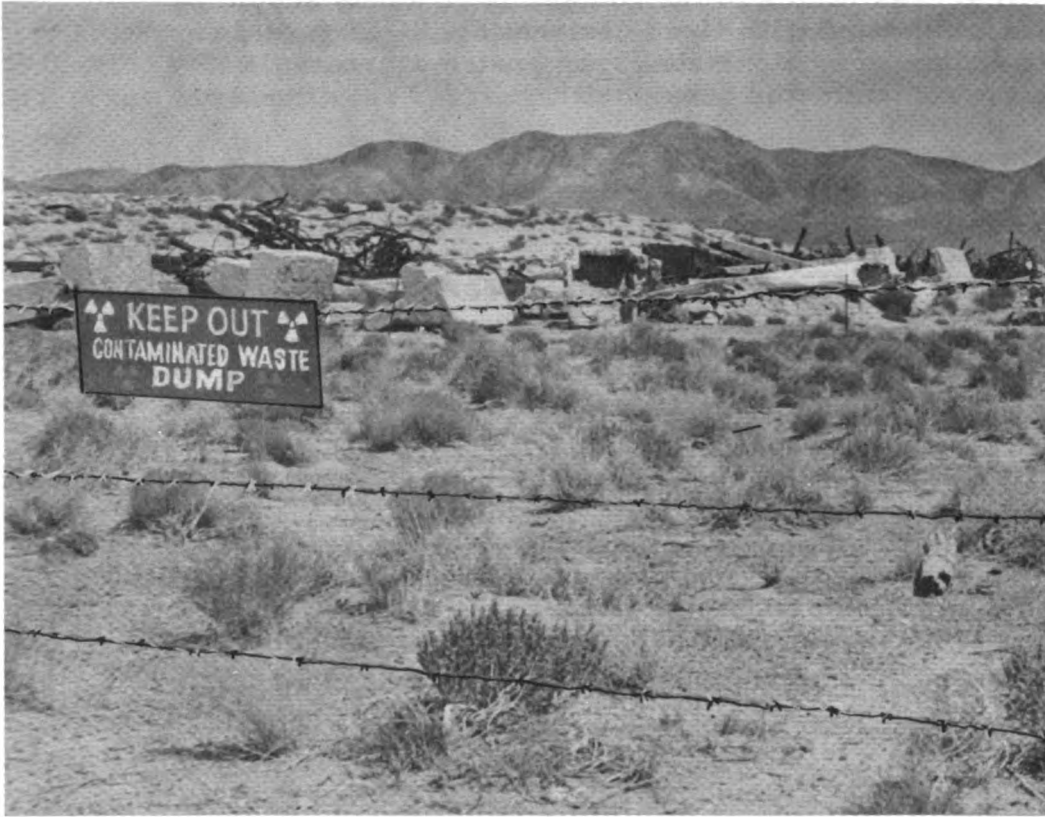
- ① Opening contaminated containers and pipelines.
- ② Washing and flushing contaminated materials and surfaces.
- ③ Action of wind or rain on contaminated surfaces.

RADIATION EXPOSURE

- ① Opening shipments and equipment containing radioactive material.
- ② Moving large objects which may be acting as a shielding material.
- ③ Transferring radiation sources to a new location.
- ④ Accumulation of liquid decontamination solution in depressions of the work surface.

Despite all safety precautions, accidents will occur. Established standard procedures for dealing with possible types of accidents are an essential part of any rad-safe plan. Appendix F contains suggested emergency procedures that are applicable to various types of radiological accidents.

DELINEATION OF CONTAMINATION AND RADIATION FIELD



After assessment of a radiological situation, it is necessary to delineate or post the area to warn personnel of the type and magnitude of the radiation and contamination. The identifying radiation symbol is a magenta colored propeller on a yellow background. A sign marked "CAUTION - RADIATION AREA" is used to delineate radiation areas. A sign marked "CAUTION - RADIOACTIVE MATERIALS" is used to delineate contaminated areas or equipment. A contaminated area can also be marked a radiation area, but a radiation area should not be marked a contamination area unless contamination is also there.

In the normal order of occurrence, a monitor will first assess a radiological situation. He will delineate the radiation and contamination zones and tag or mark contaminated equipment. He will then institute controls both to minimize the dose to personnel working in and around the area and to minimize the spread of contamination. (Chapter 3 presents detailed information on radiation monitoring.)

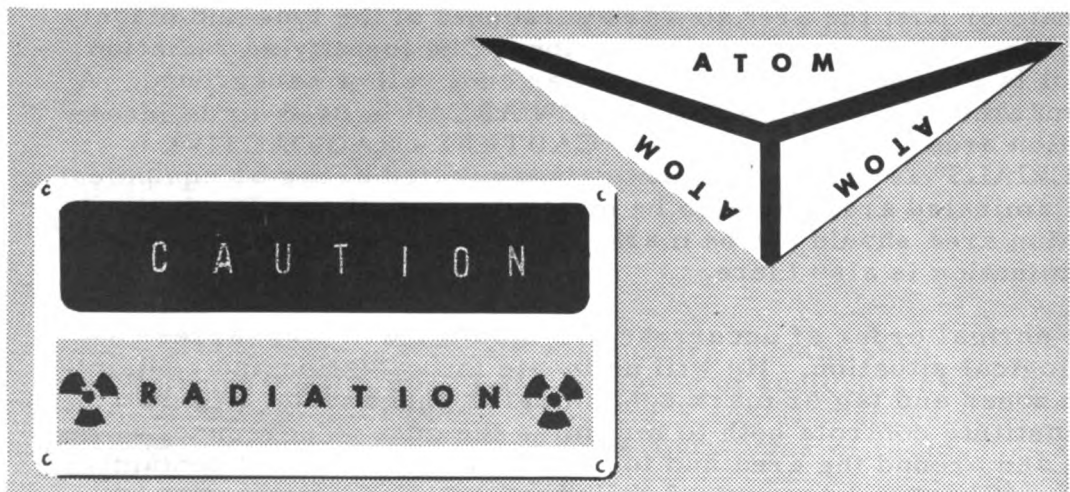
Contaminated areas should be roped off or barricaded and adequate signs posted to define the radiation zone. The use of rope for marking areas is limited to small zones of contamination or to the delineation of areas for storage of radioactive materials and equipment. Barricades or fences should be used for large contaminated areas. All access routes to the contaminated areas should be barricaded and posted with signs designating the area. Along the periphery of the zone, signs should be posted at intervals to delineate the contaminated zone.

POSTING RADIATION AREA

The monitor will delineate a radiation area by posting:

- ① A sign reading - CAUTION - RADIATION AREA.
- ② Information on type and level of radiation and the related stay-time.
- ③ Date and time of posting.
- ④ His name (in case further information is required).

Some radiation delineation signs are illustrated below:



POSTING CONTAMINATION AREA

The monitor will delineate a contamination area by posting:

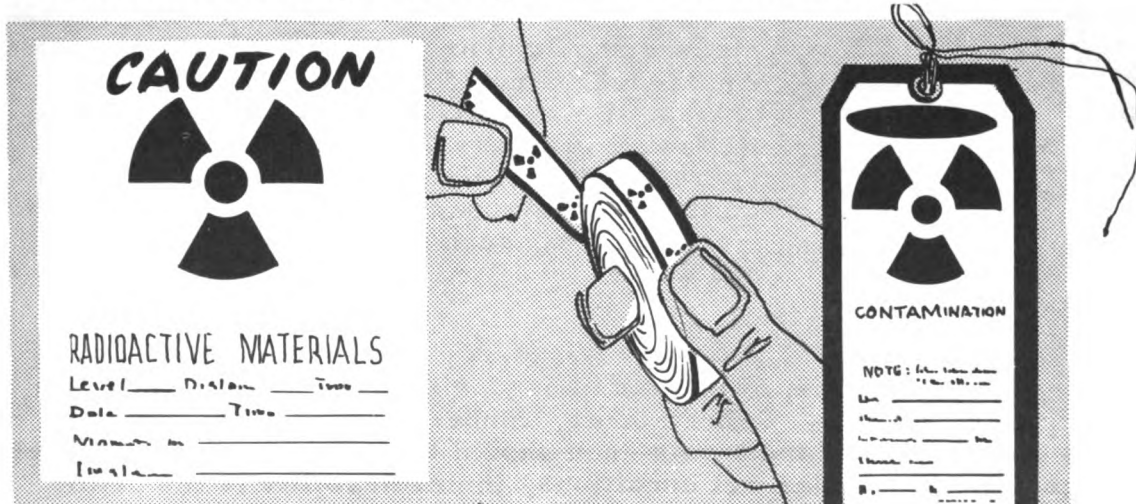
- ① A sign reading - CAUTION - RADIOACTIVE MATERIALS.
- ② Information on type and amount of radioactive material, the related dose rates, and protective equipment required for working in the contamination area.
- ③ Also a sign reading - CAUTION - RADIATION AREA - giving the dose rate and stay-time if the gamma radiation level is greater than 5 mr/hr.
- ④ Date and time of posting.
- ⑤ His name (in case further information is required).

MARKING CONTAMINATED EQUIPMENT

The monitor will delineate contaminated equipment by:

- ① Tagging the equipment with a contamination tag or marking with a radiation propeller symbol.
- ② Writing in the type and amount of radioactive material and radiation level.
- ③ Listing the handling precautions required.
- ④ Giving the date and time.
- ⑤ Leaving his name (in case further information is required).

Some contamination signs and tags are illustrated below:



PROTECTIVE EQUIPMENT AND DEVICES

Protective equipment and devices are used so that various operations using radioactive materials may be performed safely. Many of the items used are common tools, others are specially designed. Whatever the item used, its purpose is to prevent excessive radiation exposure, to control the spread of contamination and /or to prevent contamination of personnel.

REQUIREMENTS AND USE OF PROTECTIVE CLOTHING

The control of radioactive contamination requires the use of protective clothing to minimize body and internal contamination and to prevent the spread of contamination to clean areas. Military uniforms and civilian clothing provide some protection by minimizing body contact with contamination. The greater the area of the body covered, the larger the degree of protection achieved. Therefore, the criterion for radiological protective clothing is full coverage of the body by a fine-weave cloth or a plastic material. Protective clothing should be adapted to quick removal with minimum contamination transfer to the wearer. Its durability and the ease with which it can be decontaminated are important factors to consider when selecting protective clothing.

Plastic coveralls are impermeable but because they tear easily their durability is poor. A fine-weave cloth coverall is satisfactory for most operations.



Cuffs at the wrists and ankles must be secure. Sleeves should overlap the gloves at the wrists, and trousers should overlap the boots at the ankles. Both sleeve and trouser cuffs should be sealed with masking tape if the wearer is operating in heavily contaminated areas. Contamination may concentrate where articles of clothing meet, such as at the wrists, ankles, and neck.

Under wet conditions, rain gear is used with face shield or full-face mask, as necessary. Rubber boots, rubber gauntlet gloves, rain coats and trousers, and a rain hood should be utilized under extremely wet conditions. Under wet conditions, impermeability is the prime requisite of the clothing materials.

Under damp, dry, or dusty conditions, coveralls, hoods, face mask or respirator, cotton and/or rubber gloves, and boots and/or rubbers may be used. A full-face mask or supplied-air mask is recommended whenever the aerosol activity level requires respiratory protection.

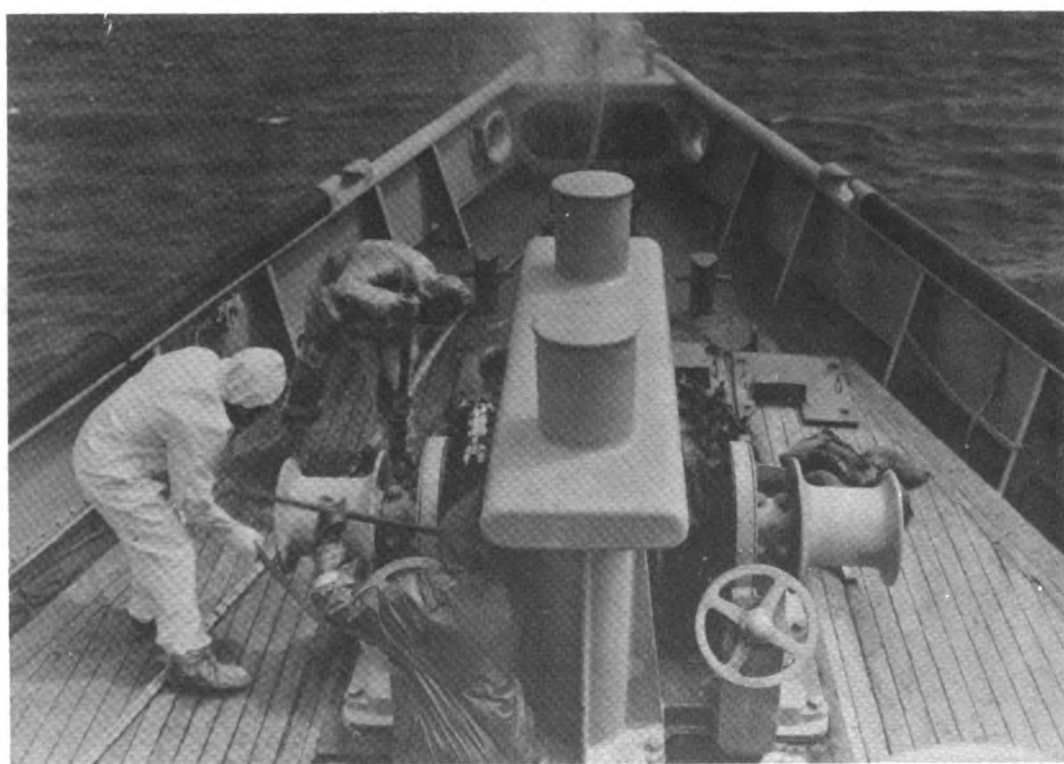
Respiratory protection is not required for outside decontamination work unless large amounts of airborne contamination are being generated in the general vicinity of the worker. Working upwind, and considering the large dilution produced by a slight breeze, masks may be necessary only in extreme situations. The working efficiency of personnel should not be unduly restricted by using more protective equipment than is needed.

THE DEGREE OF DRESSOUT SHOULD BE COMPATIBLE WITH THE CONTAMINATION POTENTIAL.

Walking through a contaminated area, for example, could require only shoe protection and handling contaminated equipment may require only gloves.



WET DECONTAMINATION GEAR



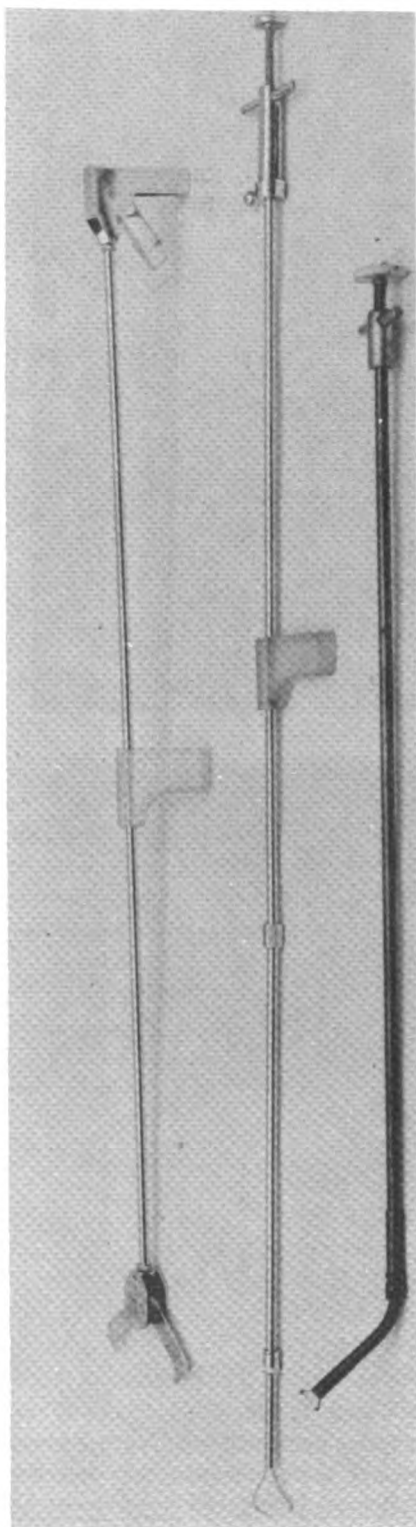
DRY WORK PROTECTIVE CLOTHING



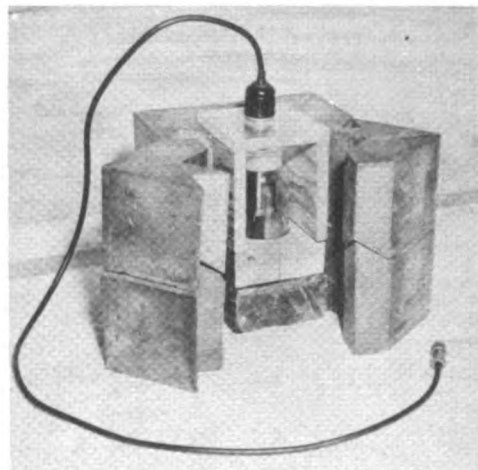
APPROXIMATE BETA DOSE REDUCTION FACTORS FOR PROTECTIVE CLOTHING

<u>ITEM</u>	<u>β REDUCTION</u>
GLOVES, SURGEON'S	30%
GLOVES, COTTON	45%
GLOVES, LEATHER (LINEMAN)	55%
COVERALLS, BROADCLOTH	30%

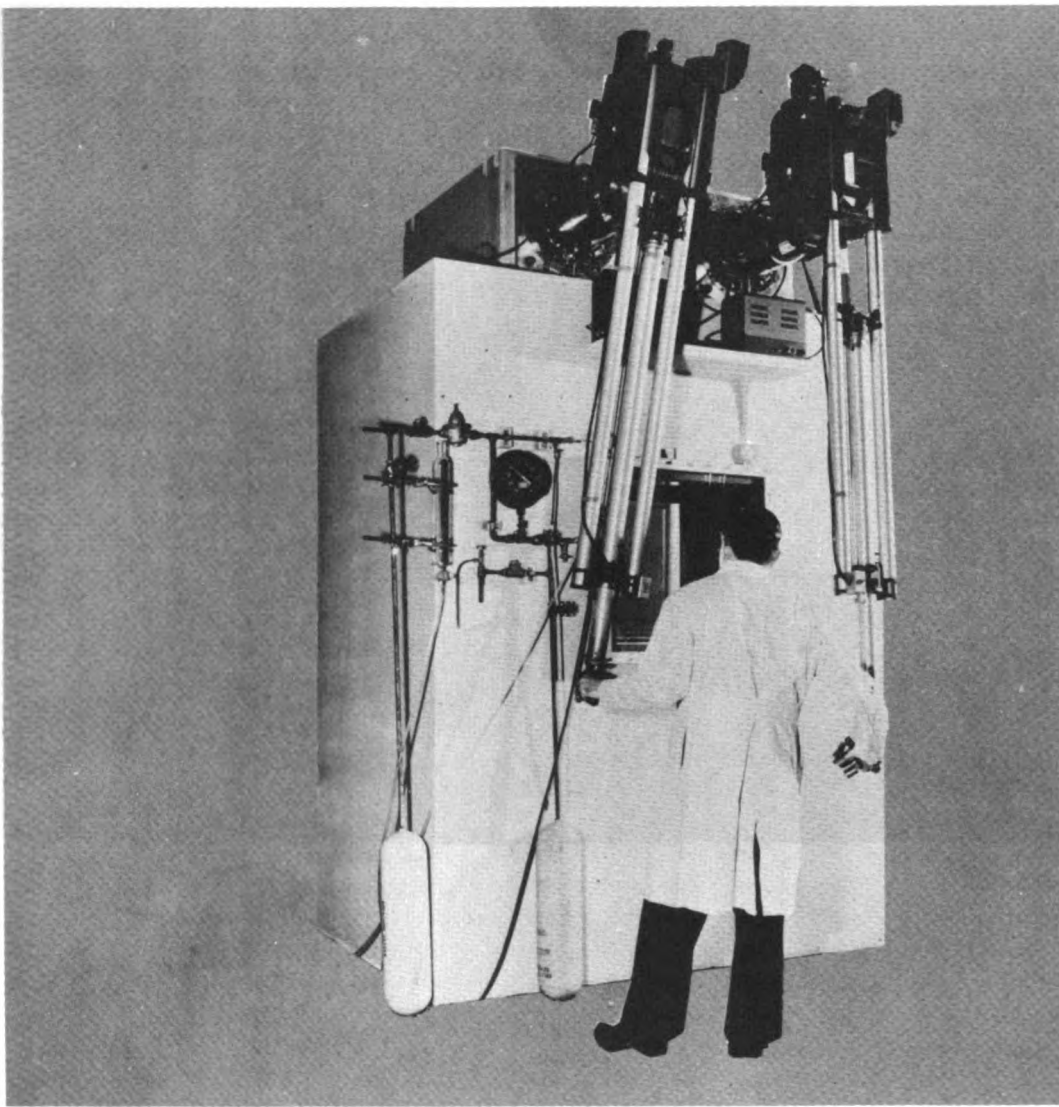
REMOTE AND SHIELDED HANDLING DEVICES



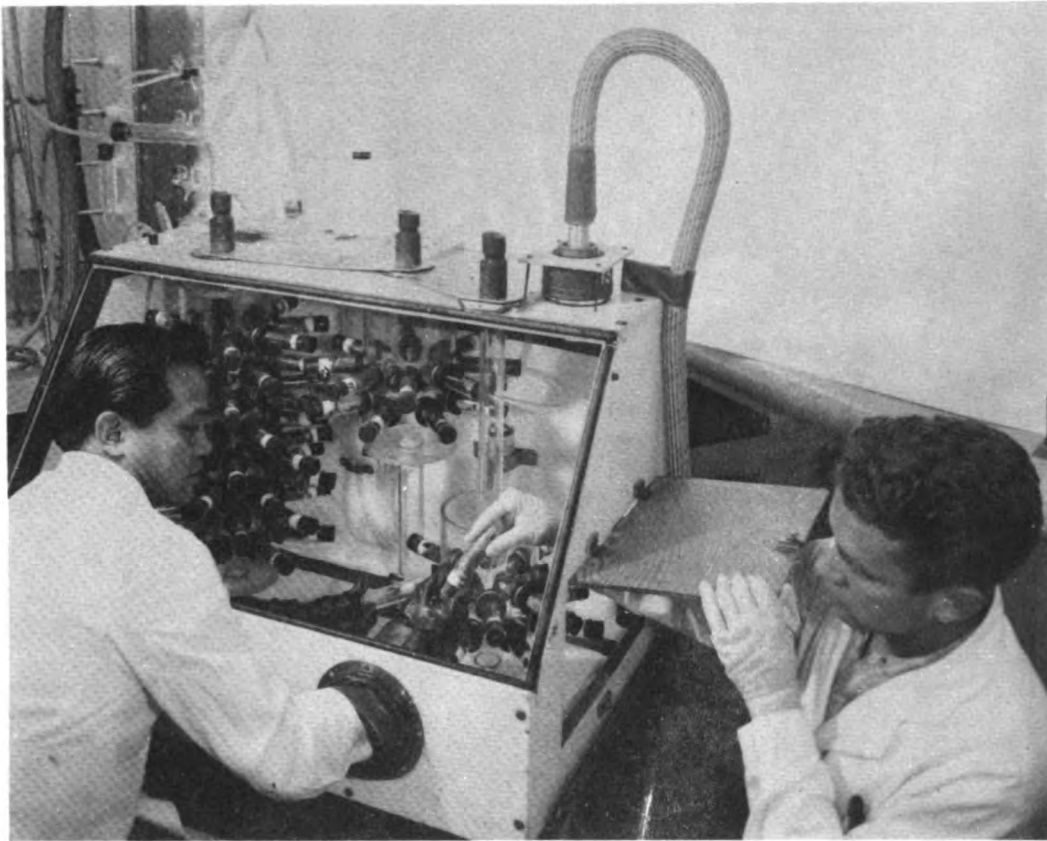
Remote handling manipulators are used to move radioactive sources or contaminated items to prevent direct contact with the radiation source. These handling devices vary from simple tweezers and pliers to intricate master-slave manipulators. By utilizing remote equipment, work on high-level gamma sources can be carried out with minimum radiation exposure.



Walls or caves for storing high-level gamma sources or for shielding radiation detectors from gamma radiation can be conveniently made out of lead bricks.



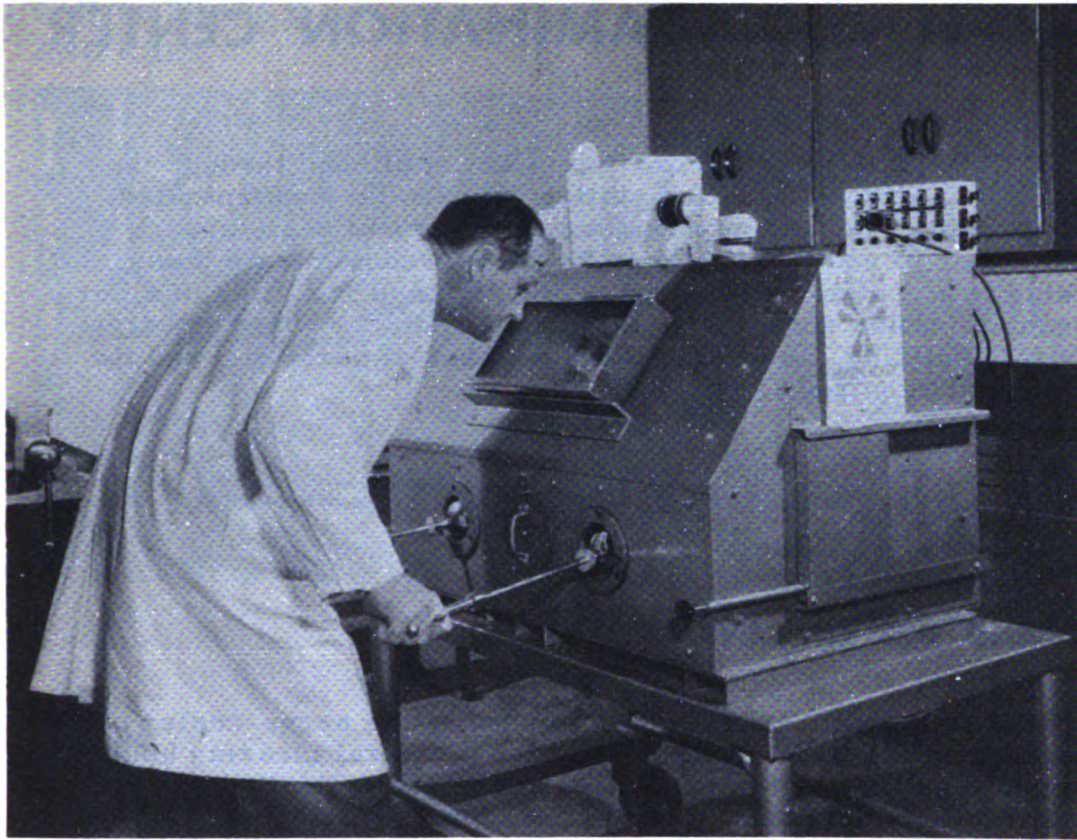
A "hot cell" may be used for handling high-level radiation sources. The hot cell is essentially a concrete cubicle with walls several feet thick to attenuate the gamma radiation. The operator looks through a window made of high-density glass or filled with transparent high-density liquid (zinc bromide solution). Sometimes visual control is had by closed channel television. Mechanical manipulators (master-slave units) reach into the cell and duplicate the wrist and finger movements of the operator. The atmosphere inside the hot cell is filtered and maintained at a negative pressure to prevent the escape of radioactive contamination.



UNSHIELDED GLOVE BOX

Since the prime requisite in handling radioactive material is to confine and control the spread of contamination, small, totally enclosed experimental facilities are often utilized. An unshielded "glove box," as shown above, can be used for alpha- or low-level beta experiments.

The boxes have holes in the front to which long gloves are attached, enabling a person to work from the outside. The box has a small fan which withdraws the air through a filtering system, maintaining a negative pressure inside the box to prevent the escape of contamination. The front of the box has a large window while the back of the box has electrical and service connections.



SHIELDED GLOVE BOX

When it is necessary to work with material emitting penetrating radiation, a lead-shielded glove box may be used. Tongs or manipulators are used instead of gloves (still called a glove box). The one shown above has a 2 inch lead shield.

The experimenter looks through a lead glass window working the apparatus inside the shielded box with the tongs or from electrical or mechanical controls outside the box. The shielded glove box, in addition to providing gamma ray attenuation, is also used to maintain a controlled atmosphere. Filters, lights, and fans are mounted externally for ease in maintenance.

PERSONNEL DECONTAMINATION CENTER

Basic ZONE CONTROL of contamination is accomplished through the establishment of a decontamination station between the contaminated area and the clean area. All personnel and equipment pass through this station either to equip them for work or to decontaminate them after working in a contamination area. The size and facilities of a personnel decontamination center may vary from a simple roped-off area to an elaborate building, according to the number of personnel and the degree of control required.

PURPOSE AND USE OF CENTER

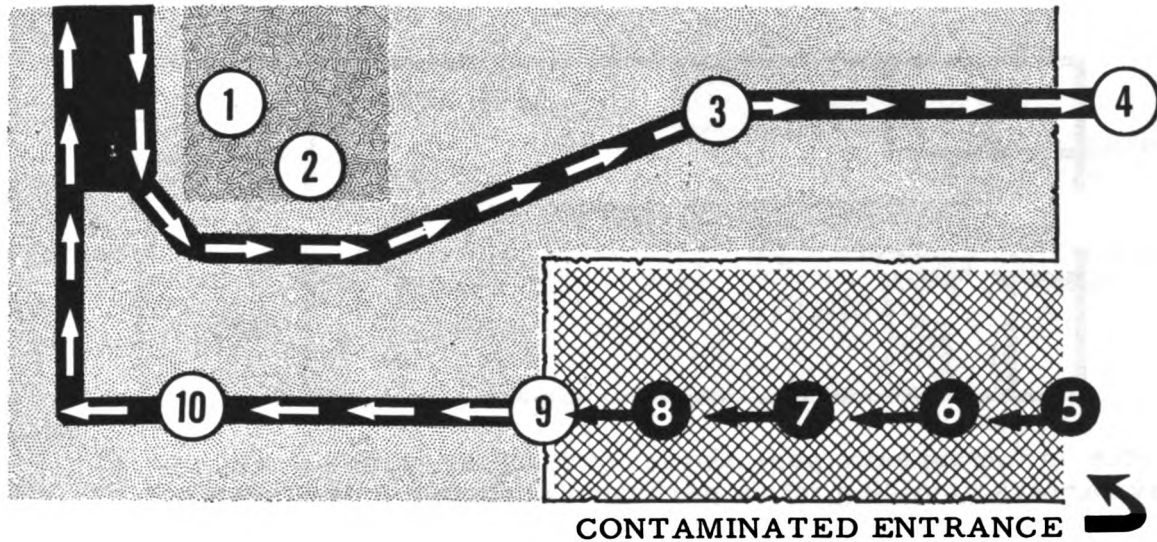
The Personnel Decontamination Center is usually the nerve-center of the rad-safe activities in the field. It is also a central clearing house for equipment required for the protection and decontamination of personnel. Instructions pertinent to the radiological situation are relayed to personnel, and film badges and pocket dosimeters and other rad-safe equipment are issued.

The principle of zone control is used within the decontamination center itself. Every effort should be made to separate the "clean" and the "contaminated areas." The figure opposite is a functional diagram illustrating the flow of personnel from the clean area to a dressout station, then on to the contaminated area where they will work. Upon return to the center, personnel are processed through the decontamination section, monitored, decontaminated as necessary and, when found "clean," permitted to dress in personal clothing to return to normal duty.

Personnel returning from the contaminated area must be processed properly to prevent spreading contamination to "clean" work areas, living quarters, and eating spaces. Each must be monitored as soon as he exits from the contaminated area. Used protective clothing must be placed in the proper containers according to the level of its contamination. Personnel must be monitored for local "hot spots" and general skin contamination.

CLEAN ENTRANCE
AND EXIT

TO WORK AREA →

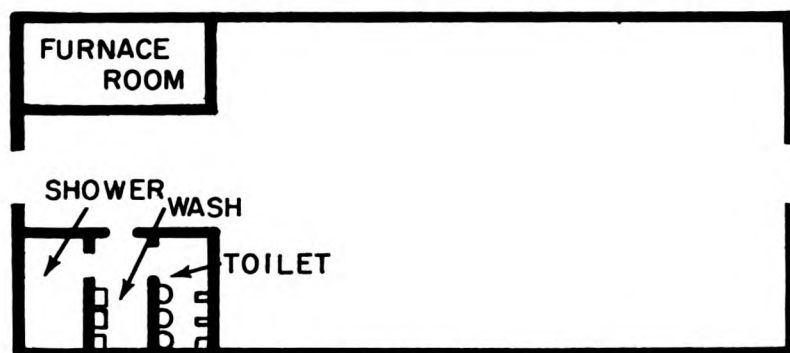


STATIONS

- ① Protective clothing and equipment storage and issue.
- ② Dosimeter issue.
- ③ Change from personal apparel to protective clothing.
- ④ Departure to work area.
- ⑤ Initial monitoring to segregate highly contaminated personnel.
- ⑥ Removal of contaminated protective clothing.
- ⑦ Monitoring to locate "hot spots."
- ⑧ Personnel decontamination.
- ⑨ Personnel monitoring check.
- ⑩ Dressing in personal clothing.

The same principles apply for processing contaminated equipment. Normally, the equipment decontamination station will be near or adjacent to the personnel decontamination station.

ARMY BARRACKS FLOOR PLAN

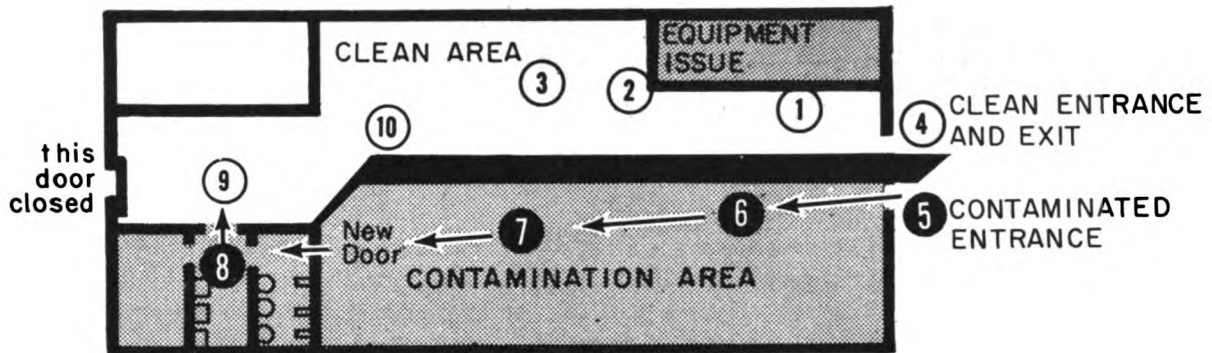


The sketch on the opposite page shows the temporary modification of an army barracks building into a personnel decontamination center. Conforming with the principles stated in the preceding section, the barracks was divided into clean and contaminated zones. A new door was cut into the toilet room wall, opening directly into the contamination area, so that contaminated personnel could be kept out of the clean area between the toilet room and the furnace room. The photograph shows the initial monitoring station through which all personnel are processed when returning from the contaminated zone.



INITIAL PERSONNEL MONITORING OUTSIDE PERSONNEL DECON STATION.

CONVERTED TO A PERSONNEL DECONTAMINATION CENTER



CLEAN

- ① Protective clothing and equipment storage and issue
- ② Dosimeter issue
- ③ Change from personal apparel to protective clothing
- ④ Departure to work area

CONTAMINATED

- ⑤ Initial monitoring to segregate highly contaminated personnel
- ⑥ Removal of contaminated protective clothing
- ⑦ Monitoring to locate "hot spots"
- ⑧ Personnel decontamination

CLEAN

- ⑨ Personnel monitoring check
- ⑩ Dressing in personal clothing.

AN EMERGENCY SHIPBOARD INSTALLATION OF PERSONNEL DECONTAMINATION CENTER

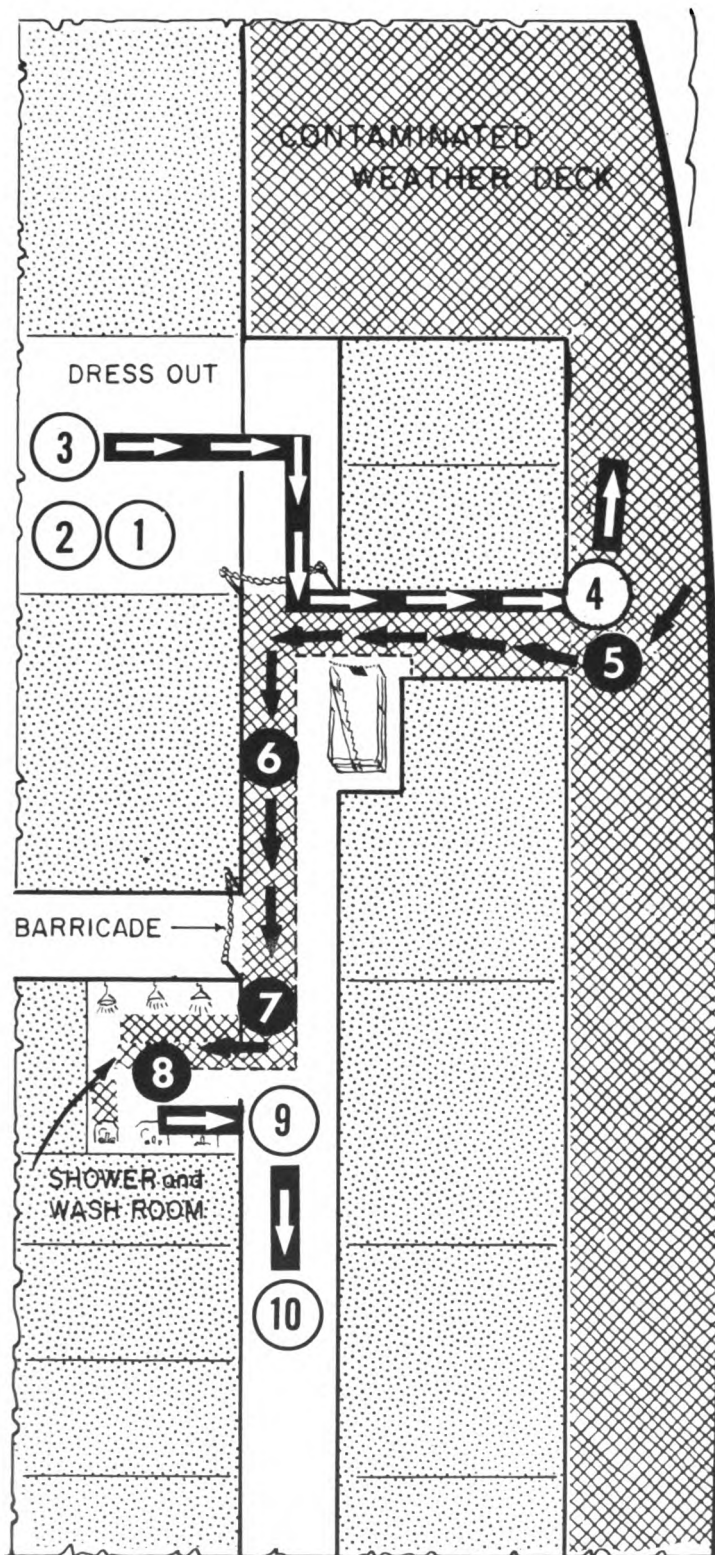
Establishing such a center aboard ship presents a unique problem because personnel cannot normally evacuate the ship. If the ship is contaminated from fallout, they have to decontaminate the ship while they are still aboard. They must live with the contamination while they bring it under control.

The interior spaces of the ship must be kept as free of contamination as practicable lest personnel get radioactive material into their bodies by eating it or breathing it. The exterior of the ship, the weather decks, will be contaminated, and it is mandatory to establish zone control of contamination in order to prevent the ingress of contamination into the interior spaces of the ship.

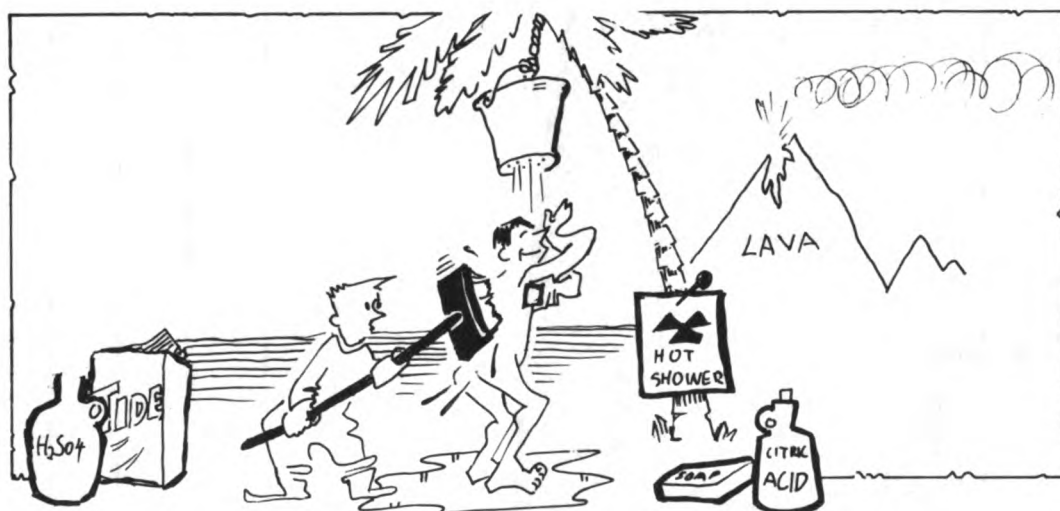
To insure better control of the flow of personnel between the clean and the contaminated areas of the ship, only a limited number of hatches should be used. Those that are used should be served by personnel decontamination stations. To have showers at these entrances to decontaminate personnel would be convenient, but usually this will not be possible. Nevertheless, a functional decontamination station can be established by having personnel remove contaminated clothing at the entrance and then proceed by a predetermined route to the nearest shower facility.

If the gamma dose rate is high, personnel monitoring may have to be done deep in the interior of the ship. Through application of zone control of contamination, a personnel decontamination station can be established on any ship even though the basic functions cannot be grouped together in the same area.

In the picture on the opposite page you are supposed to be looking down on a contaminated weather deck. The interior spaces are still clean. An emergency decontamination center has been set up. The personnel flow pattern is established so that the contaminated areas are separated from the clean areas. This will minimize the spread of contamination to other interior spaces. The function of each numbered location is the same as that listed for the converted army barracks on the previous page.



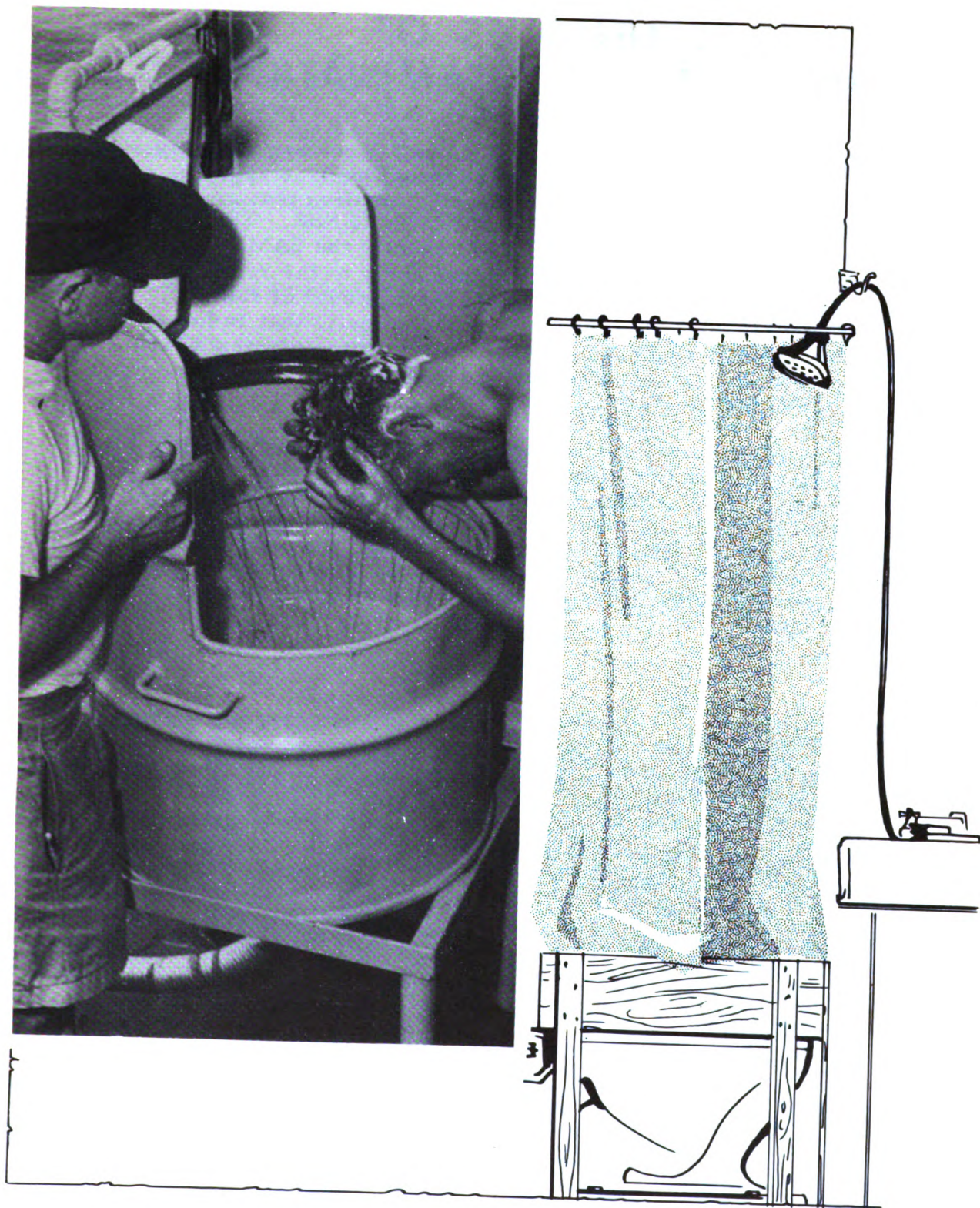
PERSONNEL DECONTAMINATION FACILITIES FOR FIELD USE



Often only the hands and face of personnel working in contaminated areas require immediate decontamination while the rest of their persons, although slightly contaminated, do not require immediate attention. Rather than process such personnel through a decontamination center, a portable hand and face washing unit can be used. Such a unit is pictured on the opposite page. It is constructed from a 55 gallon oil drum with tubing or pipe connections. Fresh or salt water may be supplied to the unit. The hands, face, and hair can be washed under the spray ring or shower head. The drain line may be run over the side of a ship or into a sump or waste container. Such a unit will be extremely valuable in removing high-level spots of skin contamination before personnel enter the decontamination center.

Some areas will be found where shower facilities do not exist. If a toilet and water are available, a shower may be constructed with canvas and plywood as illustrated. The seat of the toilet is removed and a plywood base set over the top and braced. Plywood or canvas sides may be used. If a sink with hot and cold water is available, the water can be piped to the shower head. If not, the water supply to the toilet may be diverted to supply the shower.

It should be noted that these conversions are of an emergency nature. Regulations limiting the amount of radioactive materials that may be released into a public sewer or watershed may prevent such measures except in an emergency situation.



TECHNIQUES OF PERSONNEL DECONTAMINATION

It should be understood that the aim of personnel decontamination is cleanliness, and all the precepts of good personal hygiene apply. There are two basic rules of personnel decontamination that must ALWAYS be remembered. The first is COMMON SENSE. The second is that radioactive CONTAMINATION is exactly the SAME as any other DIRT and the SAME METHODS that apply to the removal of ordinary dirt from the skin apply also to the removal of radioactive dirt from the skin. A common misconception is that radioactive isotopes are different from isotopes of the same elements in their chemical properties because they are radioactive. Nothing could be further from the truth.

The importance of removing the radioactive "dirt" stems directly from the fact that it is radioactive. It is important to remove contamination because it is continually emitting radiation that is being absorbed by the body. If the level of contamination is very high, it is important to remove the material immediately to prevent radiation burns, total body irradiation, and internal contamination. Even low-level contamination must be removed to minimize the internal contamination potential.



The **FIRST STEP** in body decontamination is **SPOT CLEANING**. Showering before local hot spots are removed could result in the spread of contamination over the entire body. Spot cleaning minimizes the spread of local contamination to clean parts of the body. In spot cleaning, cotton swabs or gauze may be used for decontamination of moist areas. Masking tape is useful to remove dry contamination. Any one of several skin cleanser preparations may be used. In stubborn cases, several preparations may have to be tried to effect complete decontamination.



The following list gives several preparations which may be used:

AQUEOUS

- ① A mixture of 50% Tide and 50% corn meal made into a paste with water. Scrub, using additional water.
- ② Mildly abrasive soap (Lava).
- ③ A 5% water solution of a mixture of 30% Tide, 65% Calgon, and 5% Carbose (carboxymethyl cellulose), used with added water.

WATERLESS

- ④ Mechanic's waterless hand cleansing cream.
- ⑤ A homogeneous cream of 8% Carbose, 3% Tide, 1% Versene, and 88% water.

The **SECOND STEP** in decontamination is **SHOWERING**, using large amounts of soap and water. Scrub the body thoroughly, especially the hands and the hair. Clean the fingernails. After the shower, monitor again and remove any residual contamination either by spot cleaning or by further showering.

Should hair contamination persist, shampoo and repeat until decontamination has been effected or until it is obvious that further shampooing will be ineffective. If it is impossible to lower the contamination to acceptable levels, then it may be necessary to clip the hair and to apply the least drastic method of the skin decontamination procedures to the scalp as outlined for the hands.

If your skin is contaminated, you don't have to act as if it were hot grease. Go where you can do the decontamination right. Even 100 rad/hr on the hands would take half a day to imitate a sunburn.

HAND DECONTAMINATION

If contamination remains only on the hands, the person may dress before trying further decontamination. The first step is to wash again, using an abrasive soap. The hands are then dried and monitored. If contamination remains, one or more of the following alternative procedures may be effective:

- ① Form a paste on the hands, using the following ingredients: water, a detergent (such as Tide), and corn meal. Massage hands with this paste for five minutes; rinse, dry, and monitor.
- ② Apply the Tide-Calgon-Carbose formula described on page 93, rub vigorously for a minute and wash off with water, dry, and monitor.
- ③ Apply the Tide-Versene-Carbose hand cream described on page 93, rub vigorously for a minute, wipe off and monitor.
- ④ Apply mechanic's waterless hand cleansing cream. Wipe dry and monitor.
- ⑤ Apply ammonium citrate or citric acid, rub together for five minutes, wash off with water, dry, and monitor.
- ⑥ Rinse or soak in a solution containing a stable isotope of the contaminant.

Scrub brush or an abrasive should not be used to a point making the hands tender. Even so, it will become necessary to restore some of the oils to the skin. Make a paste with corn meal and lanolin, or any other hand cream that may be readily available. Rub into the hands for at least five minutes and allow to remain on the hands for another five minutes. This will have a soothing effect on the skin and will prepare it for any further decontamination that might be necessary.

After the hands have been massaged with the cream mixture, wash thoroughly with a mild soap or detergent, dry, and monitor. In a large percentage of cases, the preceding steps will have effected satisfactory decontamination, but for a few cases contamination may still remain on the hands.

The reader is again reminded that THE PROCEDURES AS OUTLINED HERE APPLY TO THE EXTREME CASE OF HAND CONTAMINATION and that IN MANY CASES ACTUAL CONTAMINATION IS REMOVED BY THE APPLICATION OF ONLY THE FIRST OR SECOND STEPS. The "complete treatment" is presented here for the sake of thoroughness and to outline the steps to be taken in case someone does experience excessively stubborn contamination.

Steps ① to ④ attempt to remove the contamination by physical means, that is, to remove the contamination by washing it off. The next steps, ⑤ and ⑥ attempt to remove the contamination from the hands by CHEMICAL means, that is, to take advantage of the chemical properties of the contamination. Citrates form water-soluble complexes with many contaminants. With some contaminants it might work better to soak the hands in a basin of warm water containing one-half gram each of tartaric and citric acids. If the contaminating isotope is known, then it is possible to reduce the contamination level by treating the affected area with a stable isotope of the same element. This will effectively reduce the concentration of the radioactive atoms by exchanging with the stable atoms.

If the foregoing fails and the contamination is still dangerously high after two or three trials, one may proceed to the LAST RESORT. This method attempts to remove the contamination by removing the outer layers of skin on which the contamination has been deposited.

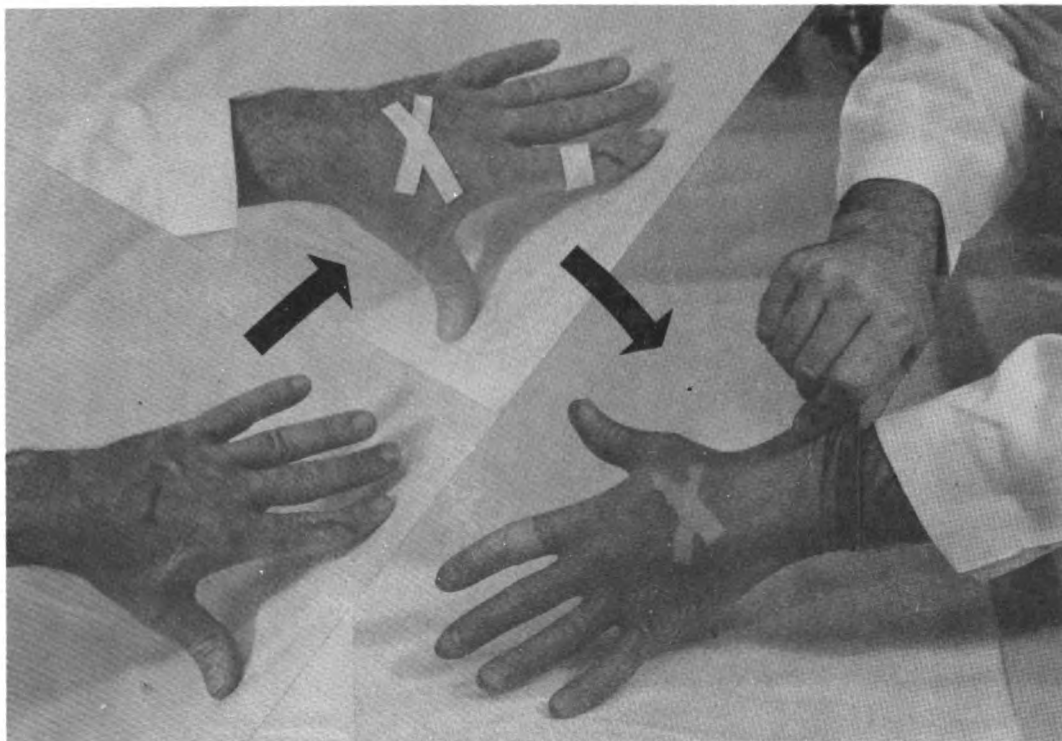
THIS METHOD SHOULD BE USED ONLY WITH A DOCTOR'S CONSENT AND UNDER HIS SUPERVISION! Rub only the contaminated area with a swab soaked with potassium permanganate and then remove the stain with sodium bisulfite (4% solution of each). If the contamination is still above acceptable levels, release the worker but suggest that he not handle or prepare food for other people and that he exercise care in handling his own food. Any person who is released with contamination in excess of the MPC should report for daily rechecks until the amount of contamination drops to permissible levels.

The above decontamination procedures are, of course, applicable to the decontamination of any skin areas. As stated above, however, the most likely skin areas to be contaminated are the hands. It should be obvious to the reader by this time that if skin contamination is encountered, the SIMPLEST AND LEAST DRASTIC MEANS OF DECONTAMINATION SHOULD BE ATTEMPTED FIRST, ALWAYS UNDER THE DIRECTION OF A MONITOR, THE RADIOLOGICAL SAFETY OFFICER, OR A DOCTOR.

The removal of contamination from the person should be as complete as practicable. However, it should be realized that the removal of the last few radioactive atoms does not justify injury to the skin. The biological significance of a small amount of contamination must be compared with the damage produced by the application of rigorous decontamination techniques. When in doubt, always consult a competent authority before proceeding with a decontamination technique that may injure the tissues.

WOUNDS OR BREAKS IN THE SKIN

If a person has a cut on his hand he should call the monitor's attention to it, before entering a contamination zone, and get it covered with impermeable tape or a glove.

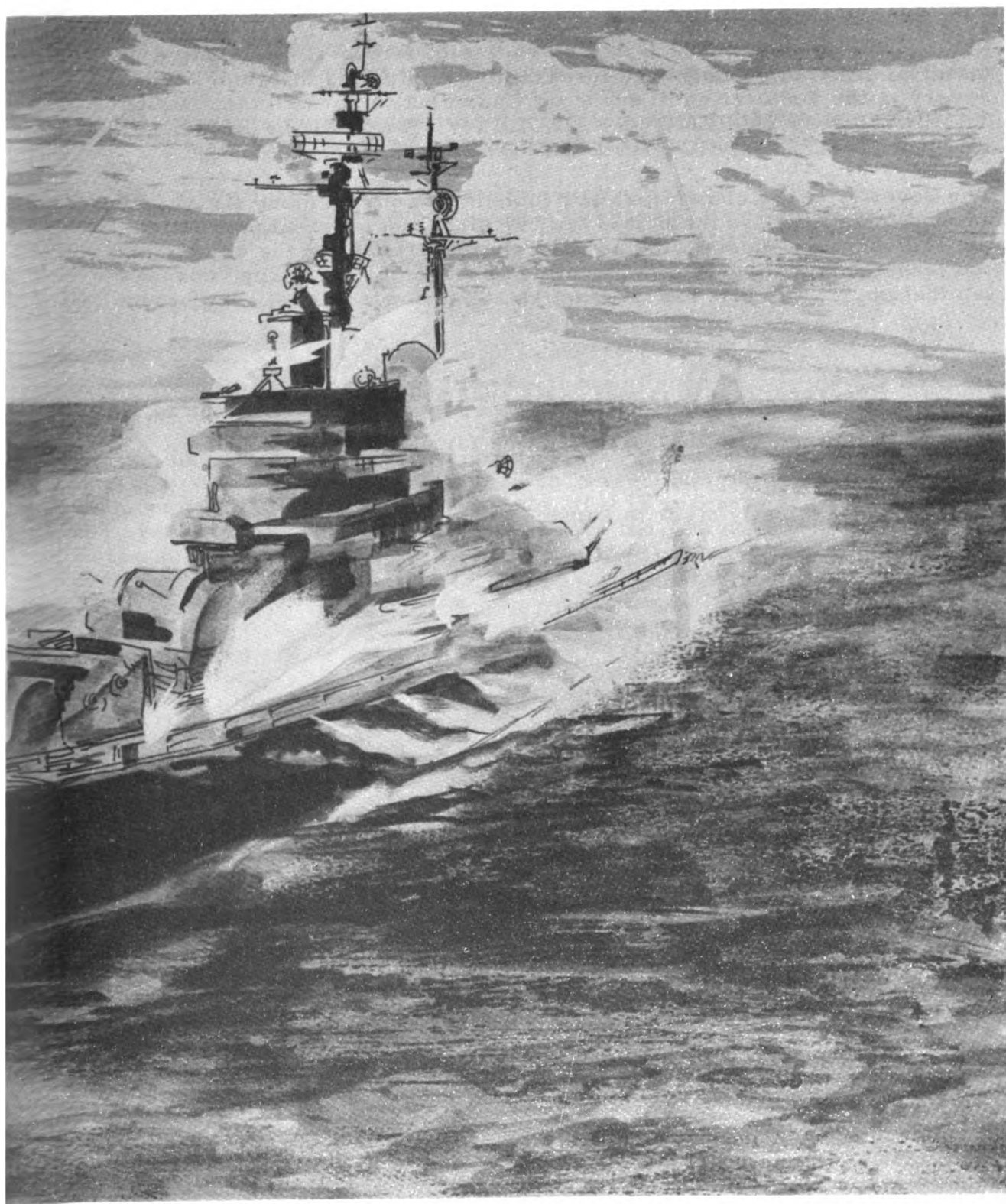


Should a person be injured or wounded while working with radioactive material, he should be removed immediately from the work area. The wound, however slight, must be monitored, decontaminated, and treated under the supervision of a doctor. In general, first aid for contaminated wounds is the same as for other wounds. The treatment should include very careful bathing of the open wound in an attempt to remove the contamination. Initial bleeding should be encouraged. Drastic decontamination procedures cannot be used on the raw tissue of an open wound. In some cases, it may be better to chance internal contamination of the body and allow the wound to heal rather than to aggravate the wound by decontamination procedures. This must be decided in consultation by the monitor and the physician.

IN THE PRESENCE OF CONTAMINATION, TREATMENT OF A WOUND REQUIRES THE ADVICE OF BOTH PHYSICIAN AND MONITOR.

WASHDOWN SYSTEM IN OPERATION



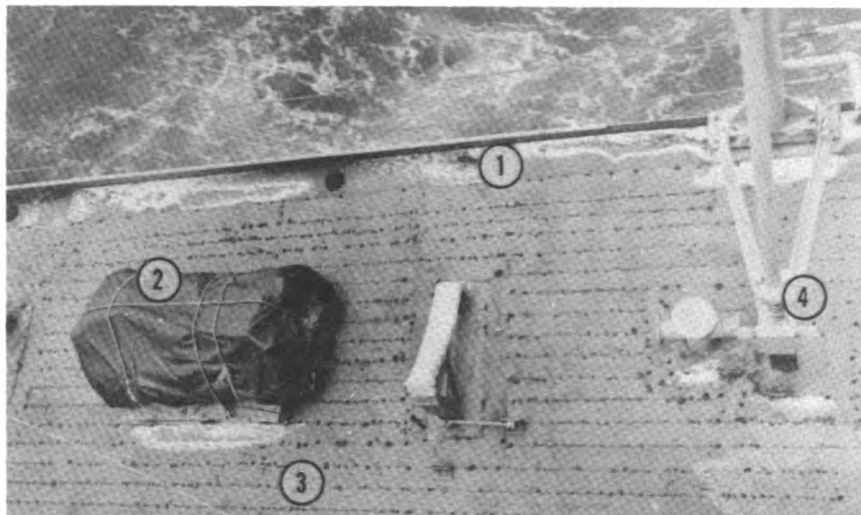


DECONTAMINATION AND RECOVERY

Radioactive decontamination is the process of removing radioactive material from an uncontrolled location to a controlled location. Recovery is the restoration of space or equipment to normal use. DECONTAMINATION IS TO REMOVE RADIOACTIVE MATERIAL. REMEMBER, RADIOACTIVITY CANNOT BE DESTROYED.

The severity of the contamination problem depends on many factors: the amount of radioactive material, the chemical and physical properties of the radioactive material, the surface characteristics of the object, and the techniques involved in the handling of these objects. The "contamination," i. e., dirt the radioactive atoms are stuck to, may be:

- ① Lying loose on the surface.
- ② Absorbed in porous materials such as rope or cloth.
- ③ Adsorbed onto the surface in the form of ions, atoms, or molecules.
- ④ Mechanically stuck to surfaces by films of oil or grease.



- ① Contamination lying loose in the scupper.
- ② Rope and canvas soak up wet contamination.
- ③ Planks are porous and tar is sticky.
- ④ Grease binds contamination.

In spite of one's best effort, contamination may be carried on to adjacent clean areas (buffer zones). These may then in turn require decontamination.

Dosage of personnel working in a contaminated area may be controlled by:

- ① Waiting for the radioactive material to decay to acceptable levels before entering the contamination area.
- ② Decontaminating the area by removing the radioactive material to a place where it will not be a danger.
- ③ Covering, as with paper or canvas, or painting over what contamination cannot be removed to keep it from spreading.

Effective dosage control can often be accomplished by waiting for the decay of short-lived isotopes in early-time fission products. Long-lived isotopes may make the waiting policy impractical and make decontamination necessary. When the general radiation has been reduced to an acceptable level, the surface decontamination might still be incomplete. Under such conditions, if it is necessary to reoccupy the area, it is proper to attempt to reduce the redistribution potential of the surface contamination by painting over it or covering it temporarily.

The DECONTAMINATION EFFECTIVENESS of a procedure is usually expressed as the ratio of the amount of radioactive material removed to the amount originally present. A decontamination effectiveness of 85% would mean that a radiation level of 100 mr/hr in a contaminated area would be reduced to 15 mr/hr.

The effectiveness of a decontamination procedure is also measured by the RESIDUAL NUMBER, the ratio of the contamination level before and after decontamination. The residual number is used as a factor to predict what contamination will be left. A residual number of 0.15 would predict a radiation level of 15 mr/hr if the radiation level before decontamination was 100 mr/hr. (Initial Radiation Level x Residual Number = Final Radiation Level.)

SURFACE DECONTAMINATION

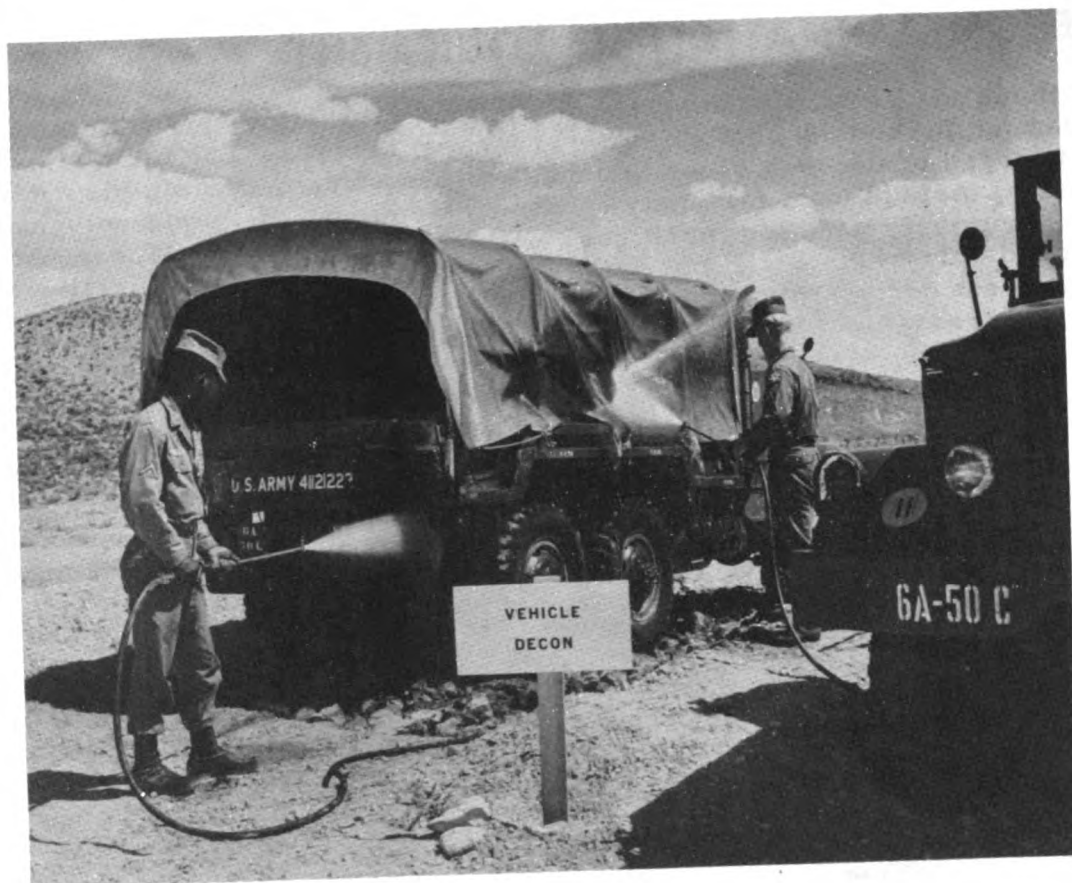
Surface decontamination is accomplished by first trying to remove *the* radioactive material by washing away the contamination. If the contamination is tightly bonded to the surface, it often becomes necessary to remove the layer of surface material containing the radioactive material. The surface may be removed by dissolving, planing, or sandblasting. The contamination is removed along with the surface. Removing the paint from a contaminated surface is usually a very effective decontamination method.

The following are commonly used decontamination methods:

- ① Flushing with water.
- ② Scrubbing with soap or detergents followed by a water flush -- vigorous action with a stiff brush will often aid decontamination.
- ③ Vacuum cleaning -- the exhaust of the cleaner must be filtered to prevent escape of contamination.
- ④ Steam cleaning.
- ⑤ Use of solvents such as kerosene or Stoddard's solvent on greasy or oily surfaces.
- ⑥ Use of a hot citric-acid solution on wood surfaces.
- ⑦ Use of a hydrochloric-citric acid mixture on metallic surfaces.
- ⑧ Surface removal, sanding, paint removal, concrete chipping, etc.
- ⑨ Bodily removal of object and disposal as radioactive waste.

Methods ① and ② are most commonly used since the materials required are usually available and, in the majority of cases, will prove to be effective.

WET METHODS DO NOT USUALLY LEAD TO MUCH OF AN AEROSOL PROBLEM - BUT WATCH OUT FOR THE SPLASHING.



DECONTAMINATION OF EQUIPMENT

Methods for equipment decontamination usually follow the same surface cleaning methods described in the previous section. The method used is tailored to the type of equipment involved. Steam-cleaning is a fairly general method used for many types of equipment. Organic solvents are commonly used for machinery with greasy or oily surfaces. Acid is used only when it will not damage the equipment. The objective of equipment decontamination is to clean the equipment for further use. Procedures which destroy its utility should be avoided.

COMMON SENSE IS THE KEYNOTE OF DECONTAMINATION.



The truck has run through a contaminated area (NPG) and is turning off to the Decontamination Center before it is used further.

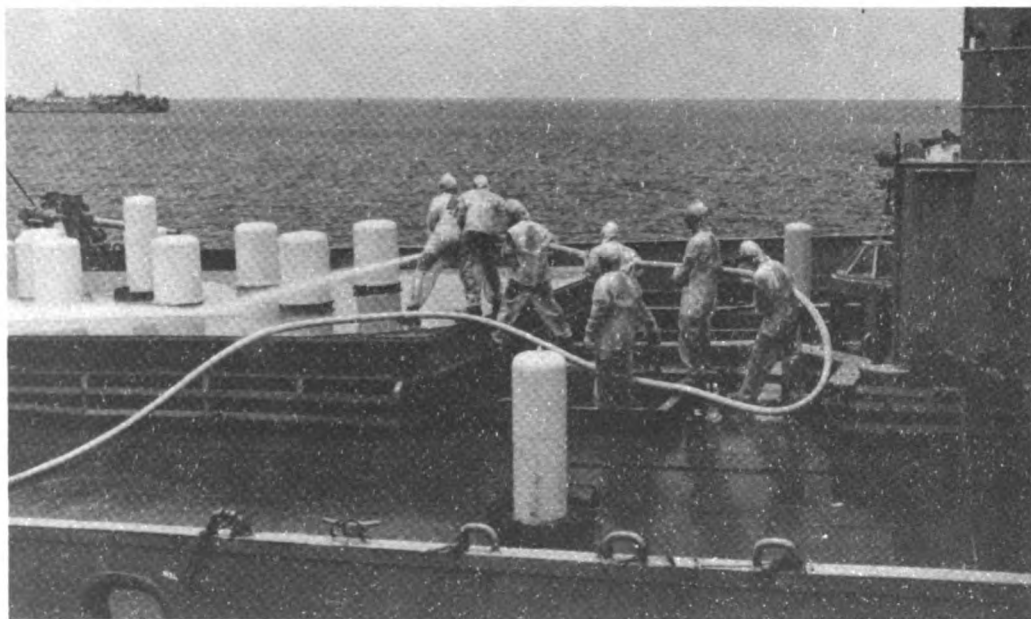


SHIPBOARD DECONTAMINATION

Aboard ship the problems are, in general, the same as those described under SURFACE DECONTAMINATION. Since the supply of decontaminating agents is limited, salt water hosing, detergents, scrubbing with brooms and swabs, and steam cleaning are the methods used. Clean, well painted surfaces, along with operation of a washdown system during a fallout period (illustrated on Pages 98 and 99) will reduce the initial contamination and minimize the effort required to remove the residual contamination.

Decontamination by fire hosing and hand scrubbing with detergent requires 5 to 7 man-teams and covers about 1500 ft² /hr. The procedure used is to firehose all surfaces working from the high surfaces down and from the upwind side if possible. Six pounds of detergent per 1000 ft² is hand-cast over the flushed area, the area is hand-scrubbed with a deck broom, followed by a water flush before the detergent dries. All hosing should be done with a solid stream hitting the surface 6 to 8 feet from the nozzle.

A steam-cleaning unit, Model FX4000, manufactured by the Sellers Corporation, produces a 150°F - 200 lb/in.² (psi) liquid jet at the rate of 100 gallons per minute when supplied with 7000 lb of steam per hour at 100 psi and 100 psi of water from a 2½ in. firehose. Detergent may be used with the unit by supplying a 1% by weight solution through the pickup tube on the unit. With the liquid jet hitting the surface 6 to 8 feet in front of the nozzle, 6 men can cover an area of 3000 ft²/hr. The liquid jet is followed by a water flush from the firehose.

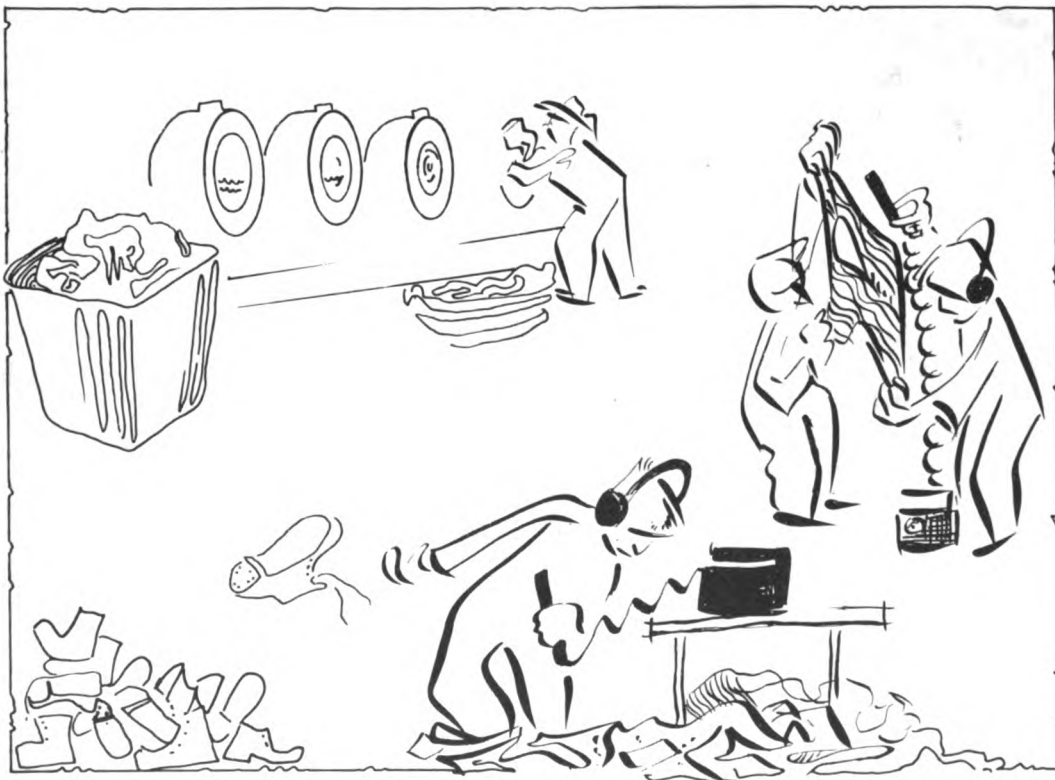


CLOTHING DECONTAMINATION

The quantity of protective clothing for a radiological operation depends upon how much the clothing can be re-used. Clothing that becomes contaminated needs laundering for decontamination as well as for cleanliness.

Radioactive contamination can be removed by the same laundering methods normally used for washing clothes. Standard, commercial-type washing equipment can be used. Laundry soap or detergent plus versene or citric acid may be used in a laundering cycle of one 5 minute rinse, two 15 minute washes, and two 10 minute rinses. After drying, each garment must be monitored. All garments still above acceptable limits must be rewashed. Clothing remaining above permissible limits (see Chapter 4) after repeated washings should be disposed of as contaminated waste.

Shoes are not ordinarily launderable. Shoe soles may be decontaminated by sanding off a thin layer of sole leather. Contaminated rubber clothing such as boots, overshoes, and rain gear often may be decontaminated by water-flushing. Decontaminated respiratory equipment should also be given an alcohol rinse for sanitary reasons.



CONTAMINATION CONTROL



CONTROL OF RADIOACTIVE CONTAMINATION IS ONE OF THE MOST IMPORTANT FUNCTIONS IN RADIOLOGICAL SAFETY. The production, use, and final disposition of all radioactive material must be carefully planned and controlled. Radioactive materials are sometimes accidentally or intentionally (weapon testing) released from a controlled environment. This radioactive contamination is of major concern because we may have to reclaim the area to prevent the spread of contamination to undesirable locations. The fundamental criterion is ZONE CONTROL. The contaminated area is restricted and rad-safe procedures are established for all personnel and equipment entering or leaving the contamination area (through a control point) to prevent the spread of contamination between the clean and the contaminated zones. Controlled areas may range from a very large piece of land to a small laboratory room.

SHIPBOARD CONTAMINATION PROBLEMS

Surface conditions will materially affect the adhesion of the contamination. Rough and porous surfaces will hold more contamination than will smooth, hard surfaces. Shipboard structural elements will materially affect contamination levels. Elements such as: (a) gun placements, (b) hatches, (c) ventilators, (d) radar, (e) wooden decks, and other shipboard features will increase contamination potential.

The major problem aboard ship is to maintain the division between clean and contaminated areas. Transfer of contamination must be controlled to maintain the integrity of the clean areas. Contaminated areas should be delineated by the roping off and posting of the areas.

CONTAMINATION OF SHIP'S COOLING SYSTEMS

Many vital pieces of shipboard machinery are cooled by sea water either directly or through heat exchangers. Conditions may arise from fallout or subsurface weapon detonations that will contaminate the sea water. All unnecessary cooling water intakes should be secured when passing through contaminated waters. The sea water side of the cooling systems operated in a contaminated sea should be monitored and labeled with the appropriate signs. All radiological information should be logged in case work should later have to be done on contaminated systems. Decontamination of these systems should be carried out as required. Maintenance or repair of such systems may present a new contamination or radiation problem when such systems are dismantled.

TRACKING AND SPREADING OF CONTAMINATION

Access to contaminated areas must be controlled to prevent the transfer of contamination to clean areas. All persons must wear adequate protective clothing. Protective clothing must be removed and personnel and equipment must be monitored to maintain the zone control of contamination. When contamination is located on a piece of equipment, it is necessary to evaluate the possible spread of contamination to surrounding areas before the equipment is taken out of the zone. If the piece of equipment will spread contamination, it must be placed in a controlled area, decontaminated, or packaged in such a way as to prevent spread of the contamination.

AIRBORNE CONTAMINATION PROBLEMS

Areas of contamination which are dusty should be moistened to minimize generation of radioactive dust particles by wind and traffic. Masks or respirators must be worn by all personnel in an area where there is airborne contamination exceeding the MPC's (see Chapter 4).

Personnel and equipment moving through dusty contaminated areas, or working there, will produce airborne contamination by stirring up and resuspending the dust. The amount of resuspended radioactive material depends on such factors as the surface condition, specific activity per unit area, type of work being performed, weather conditions, etc. The results of a study of aerosol resuspension factors derived from operations in both confined and open spaces (personnel and earth-moving equipment working in radioactively-labeled brick and mortar dust in bombed city debris) are presented in the following table:

Operations in	Surface Activity	Aerosol Concentration	Resuspension Factor
Open Areas	$1 \mu\text{c}/\text{cm}^2$	$2 \times 10^{-8} \mu\text{c}/\text{cm}^3$	$2 \times 10^{-8} \text{ cm}^{-1}$
Confined Spaces	$1 \mu\text{c}/\text{cm}^2$	$4 \times 10^{-7} \mu\text{c}/\text{cm}^3$	$4 \times 10^{-7} \text{ cm}^{-1}$

In normal situations, wind action in open spaces and ventilation in closed spaces will remove the surface contamination so that an equilibrium air contamination may not exist. The aerosol MPC's are based on continuous exposure and equilibrium concentration. Therefore, it is recommended that the aerosol resuspension factor of $4 \times 10^{-8} (\text{cm}^{-1})$ be used for both open and closed spaces.

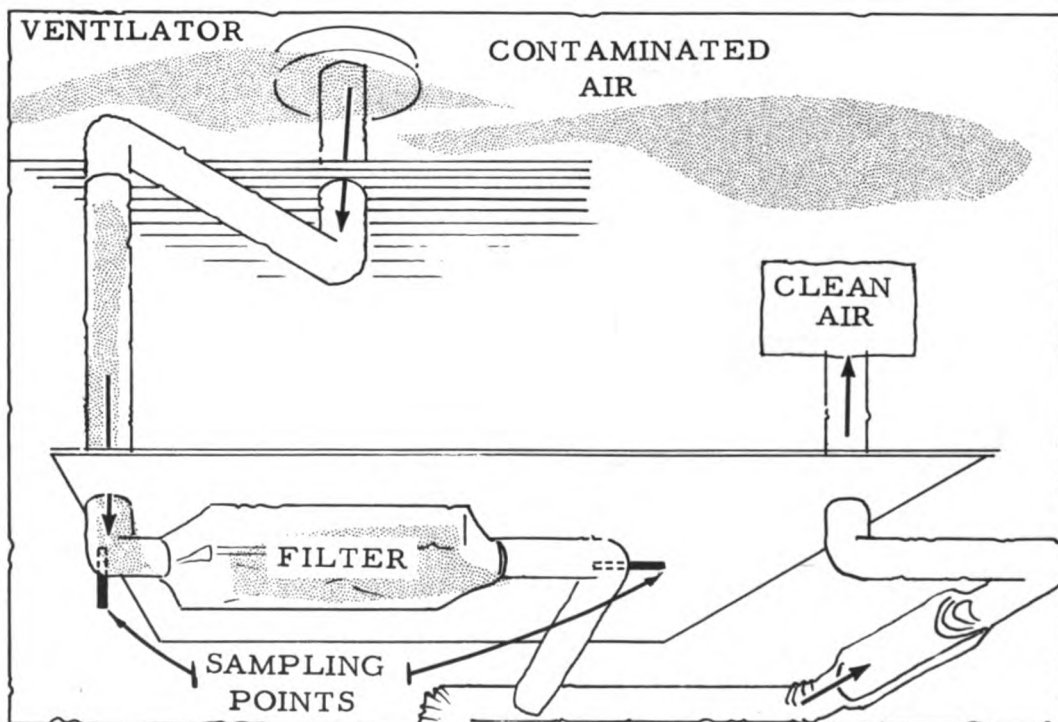
For example, the expected aerosol concentration for heavy work in an open field with a surface contamination level of $80 \mu\text{c}/\text{cm}^2$ is:

$$(80 \mu\text{c}/\text{cm}^2) \times (4 \times 10^{-8} / \text{cm}) = 3.2 \times 10^{-6} \mu\text{c}/\text{cm}^3 \text{ or } 3 \times 10^{-6} \mu\text{c}/\text{cc}.$$

The use of the above resuspension factor is good only for an order of magnitude estimate.

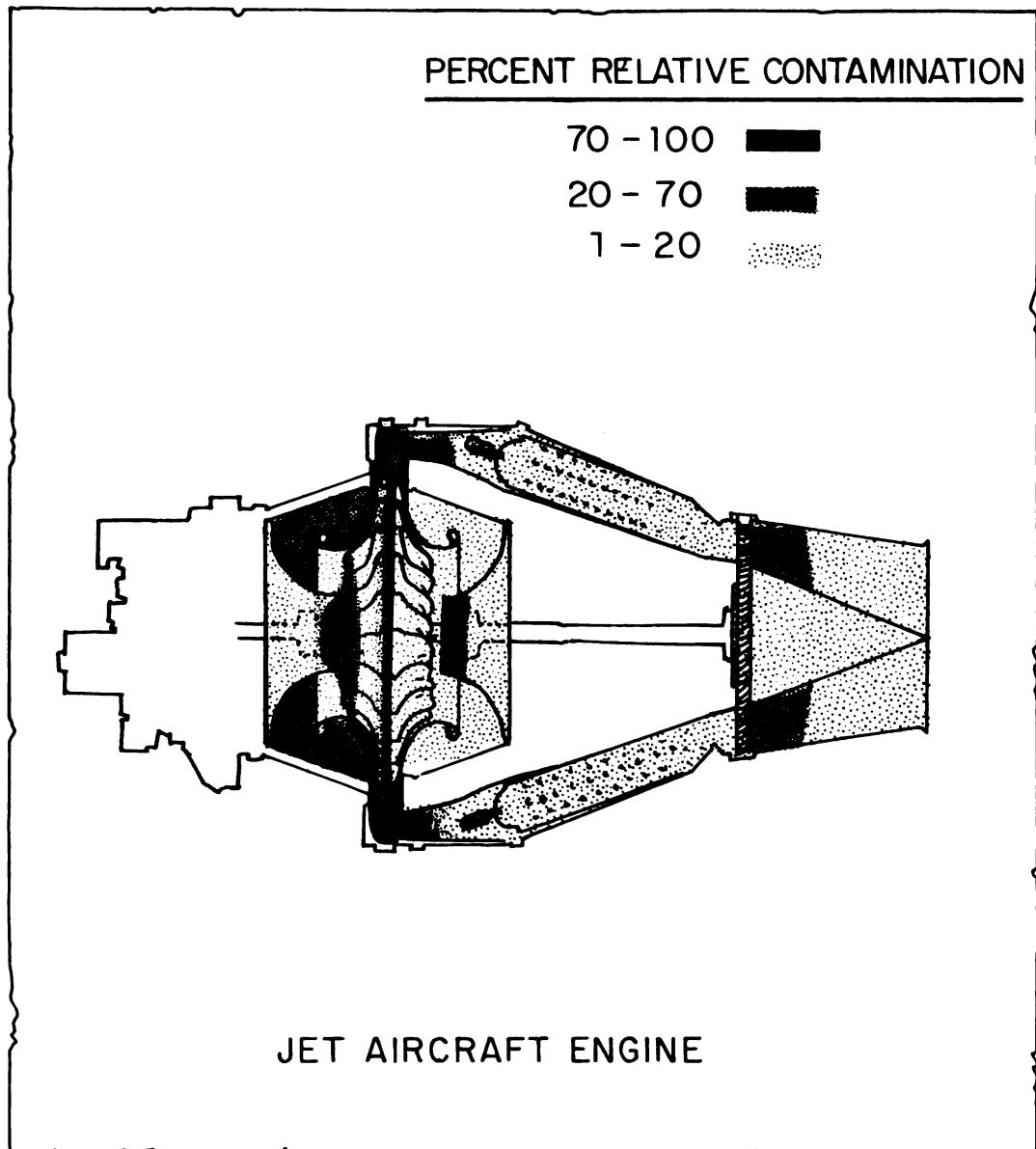
During periods of excessive fallout, all personnel should remain under cover if possible. Otherwise, protective clothing, including masks or respirators, should be worn. During the fallout period aboard ship, all ventilation not absolutely required may be shut down to minimize contamination of the interior of the ship. Airborne radioactive material carried into the ventilation system and distributed in spaces below deck may create a contamination problem. All ventilated areas should be monitored at the end of the fallout, and contaminated areas delineated and decontaminated as required. The use of temporary ventilation systems aboard contaminated ships undergoing repairs requires special consideration.

Air exhausts should be located in such a manner that the contaminated air is not carried to a location where persons are working. No ventilation system suspected of being contaminated should be operated unless clearance has been granted by the radiological safety officer or by other technically qualified personnel responsible for radiological safety.



DISMANTLING CONTAMINATED EQUIPMENT

The combustion chambers of boilers and internal combustion engines may become highly contaminated when operated during fallout. Maintenance or repair on these units will require monitoring since hidden contamination and radiation may be exposed as the units are dismantled. The following figure shows where the contamination stacked up in a jet engine that was used in traversing a fallout cloud.

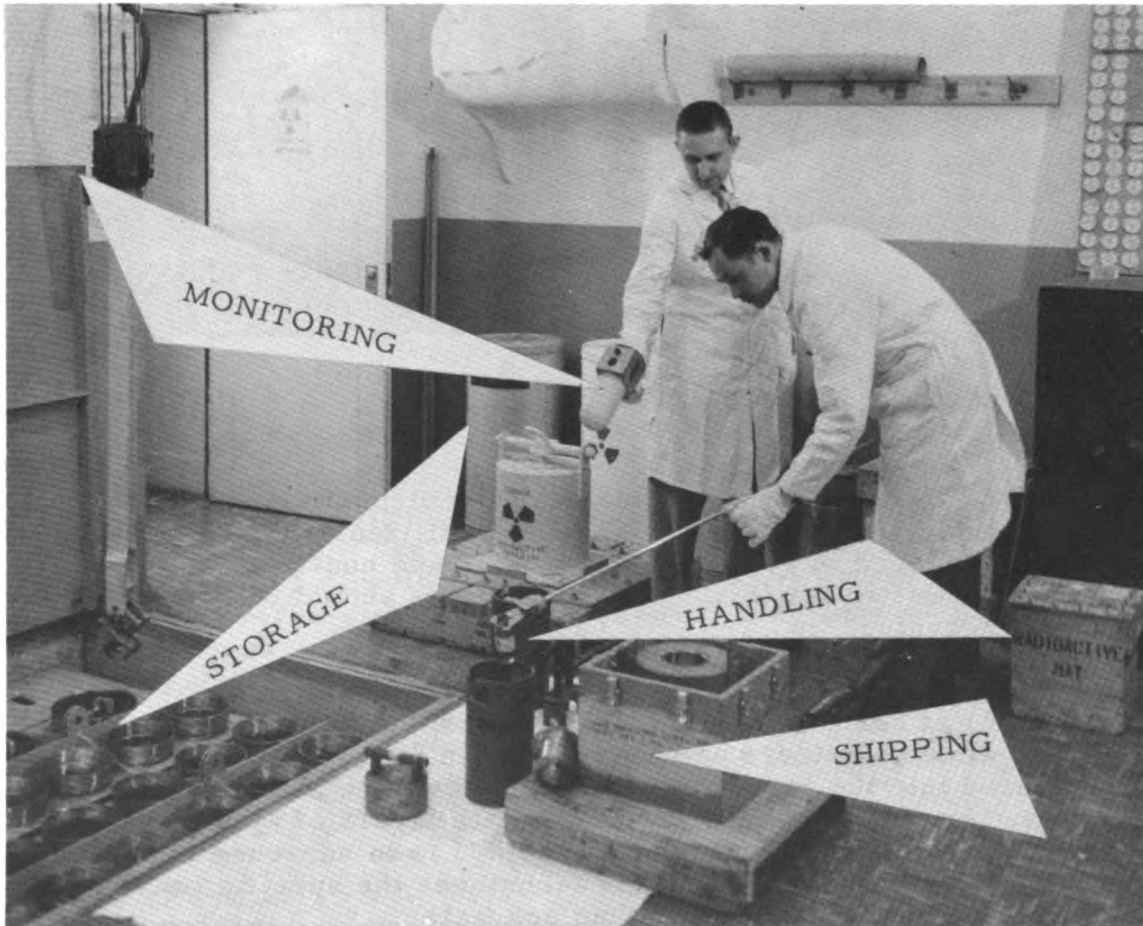


STORAGE AND TRANSPORTATION OF RADIOACTIVE MATERIAL

Whenever possible, radioactive material should be stored in sealed containers and then shielded with appropriate materials so that the intensity will be reduced to less than 200 mr/hr at the surface of the container and less than 10 mr/hr at 1 meter from the container. The removable contamination on the surface of the container should be less than 350 d/m/cm². Adequate radiation caution signs should be plainly visible at all times.

Liquid material should be packaged in a double container with sufficient absorbent material to take up all the liquid if the container should break. Solid material which is dusty should be packaged in a sealed container to prevent the spread of radioactive dust. Sealing in plastic bags is a way to prevent the spread of contamination.

Radioactive material to be shipped must meet the ICC Shipping Regulations Section 73, 393, Packaging and Shielding.



WASTE DISPOSAL

RADIOACTIVE WASTE MATERIAL

Is
a problem
in
STORAGE
and
DISPOSITION



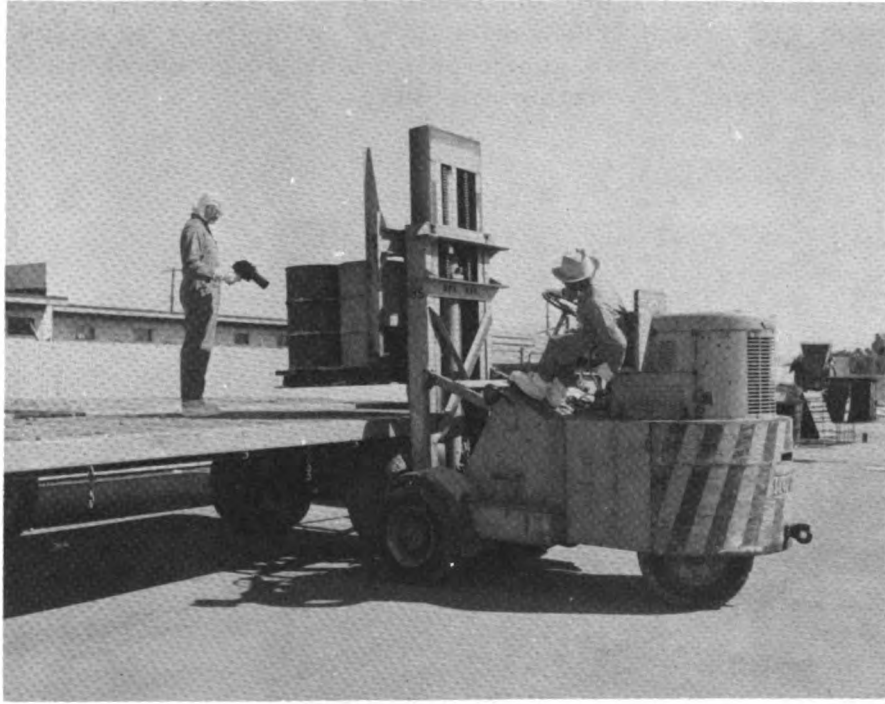
Solid waste may be placed in sealed containers for disposition. If at all possible, a double-sealed container should be utilized. Liquid material should be placed in sealed non-corrosive and non-breakable containers such as plastic bottles. Acids and alkalis should be neutralized before packaging.

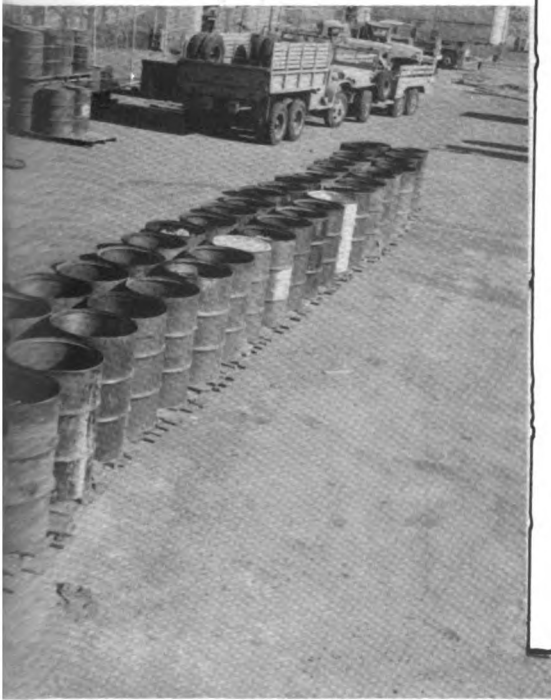
In general, there are two methods for disposing of radioactive waste, namely, on land or at sea. For SEA BURIAL, waste material may be packaged in 30-gallon containers and then placed in 55-gallon drums. Concrete is poured into the remaining space to weight the material so that it will sink. Another technique is to alternate layers of waste and concrete in a 55-gallon container. A third method is to surround the container with concrete. For all of these techniques the specific gravity of the filled container must be greater than sea water.

Bottles or cans holding liquid waste are placed in 55-gallon drums, and concrete is cast around them to seal and weight the drums. If the activity is not too high for safe dilution in the ocean, 55-gallon containers can be preweighted with sand, the liquid waste being added through the bung hole, and afterwards sealed. Weighting may be added to the outside of the container with a gunite unit. The weighted waste is then dumped at sea in over 1000-fathom depths.

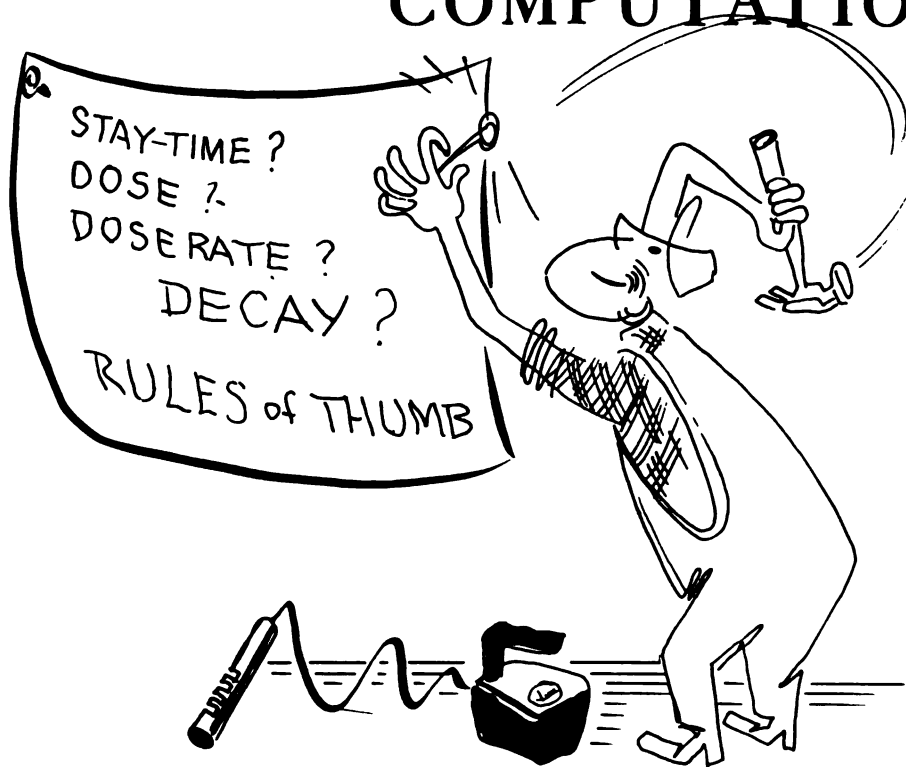


Locations for LAND BURIAL must be kept under control for an indefinite length of time. The same procedure for packaging is followed with the exception of weighting. The material is placed in a deep trench and covered with earth. The selection of the land burial site depends upon environmental conditions, such as the water table, population, etc.





HEALTH PHYSICS COMPUTATIONS



THE BASIC FUNCTION OF RADIOLOGICAL SAFETY IS TO MINIMIZE AND CONTROL THE EXPOSURE TO EXTERNAL AND INTERNAL SOURCES OF IONIZING RADIATIONS. This section presents the basic relationships that every monitor must know to calculate dose and stay-times (safe working times) in the presence of external sources and mixed fission products. Appendix D tabulates conversion factors. Appendix E presents graphs and tables for estimating dose, dose rate, and shielding thicknesses.

THE FOLLOWING FORMULA MAY BE USED TO ESTIMATE, WITHIN 20%, THE DOSE RATE OF A GAMMA POINT SOURCE.

$$D_1 = 6 \text{ CE r/hr one foot from source}$$

Where C = Strength of source (in curies)

and E = Sum of all gamma energies of the isotope
(in Mev).

Problem: The dose rate 1 foot from a 5 curie Co⁶⁰ point source would be estimated as follows:

Since Co⁶⁰ emits two gamma rays per disintegration, of energies 1.1 Mev and 1.3 Mev, the sum of the gamma ray energies (E) equals 1.1 + 1.3 = 2.4 Mev. The dose rate 1 foot from the source is given by:

SOLUTION: $D_1 = 6 CE$

$$D_1 = 6 \times 5 \times (1.1 + 1.3) = 6 \times 5 \times 2.4$$

ANSWER: $D_1 = 72 \text{ r/hr}$ 1 foot from source.

ANOTHER USEFUL FORMULA FOR CALCULATING DOSE RATE
FROM A POINT SOURCE IS THE INVERSE-SQUARE LAW:

$$D = D_1 / r^2$$

Where D_1 = Initial dose rate at one foot

r = Distance from source in feet

and D = Dose rate at a distance (r) from source.

Problem: If the dose rate 1 foot from a point source is measured to be 27 r/hr, calculate the dose rate 3 feet from the source.

SOLUTION: $D_1 = 27 \text{ r/hr}$

r = 3 feet from source

D = Dose rate 3 feet from source

$$D = \frac{D_1}{r^2} = \frac{27}{3^2} = \frac{27}{9} = 3 \text{ r/hr}$$

ANSWER: $D = 3 \text{ r/hr}$ 3 feet from source.

A MORE GENERAL FORMULA FOR CALCULATING THE DOSE RATE FROM POINT SOURCES IS GIVEN BY:

$$D_a = D_b \left(\frac{r_b}{r_a} \right)^2$$

where D_a = calculated dose rate at distance a from source
 D_b = dose rate measured at distance b from source
 r_a = distance a from source
 r_b = distance b from source.

PROBLEM: Calculate the dose rate one-half foot from a point source whose dose rate is 50 r/hr at 4 feet.

SOLUTION: $D_b = 50 \text{ r/hr}$
 $r_a = 1/2 \text{ foot}$
 $r_b = 4 \text{ feet}$
 then $D_a = 50 \left(\frac{4}{1/2} \right)^2 = 50 \times (8)^2 = 50 \times 64 = 3200 \text{ r/hr}$
ANSWER: $D_a = 3200 \text{ r/hr.}$

STAY-TIME CALCULATIONS

IT IS MANDATORY THAT EXPOSURE TO RADIATION BE MINIMIZED. Since certain duties involve exposure to ionizing radiation, time limits (stay-times) must be established for working in radiation zones. Personnel working in a radiation field must limit their stay-time so that they do not exceed the established permissible dose. The stay-time is given by

$$\text{STAY-TIME} = \frac{\text{Permissible dose}}{\text{Dose rate}}$$

where permissible dose is the amount of radiation exposure established for the particular job, and the dose rate is the radiation intensity in the work area.

PROBLEM: Suppose a person had to perform an experiment using a sealed gamma-emitting isotope which subjected the experimenter to a gamma dose rate of 720 mrad/hr. What would be the maximum stay-time in minutes so as not to exceed a dose of 300 mrem? (Note: 1 mrad of gamma- or X radiation is equivalent to 1 mrem.)

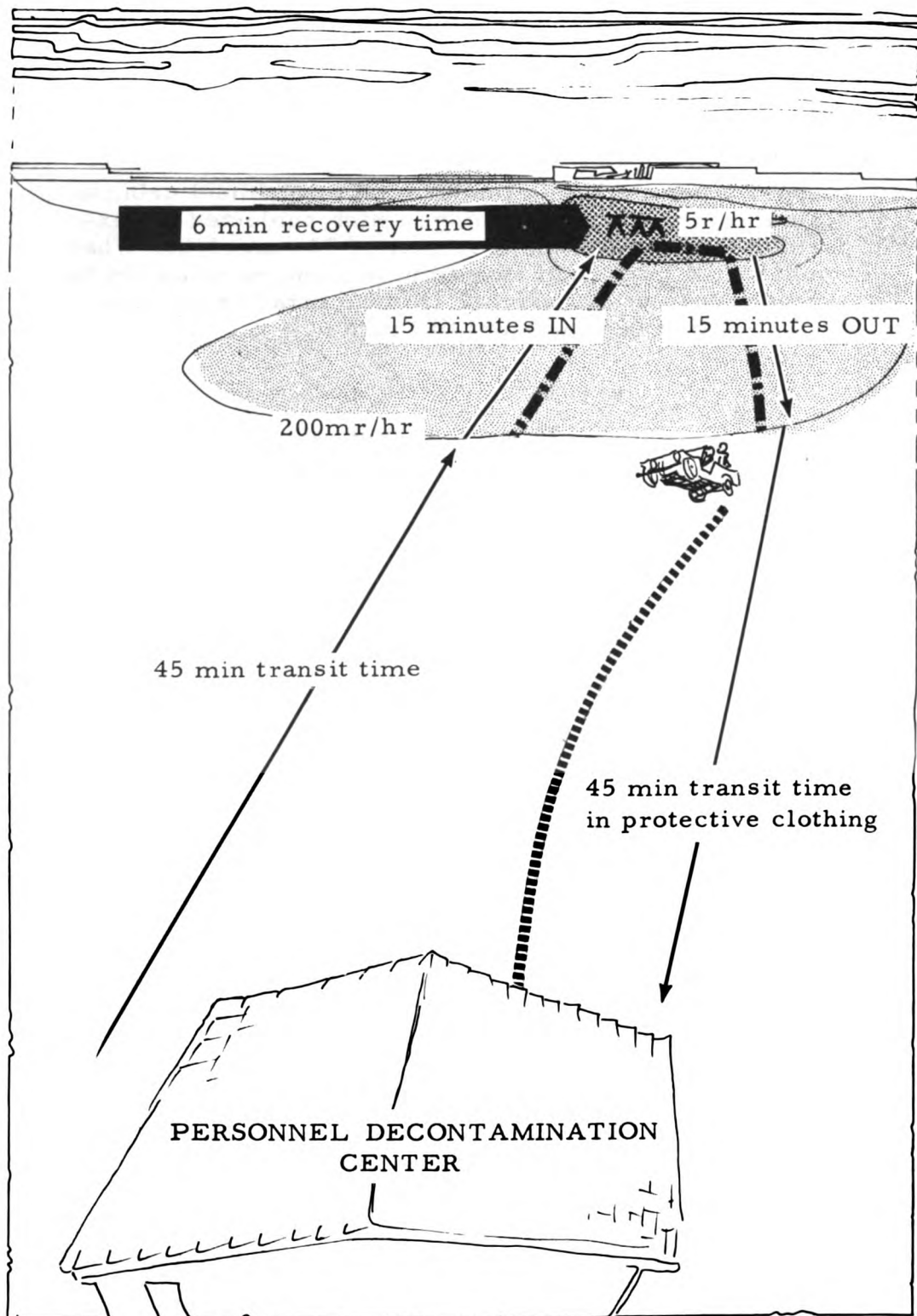
SOLUTION:

$$\text{Stay-time} = \frac{\text{dose}}{\text{dose rate}} = \frac{300 \text{ mrem}}{720 \text{ mrad/hr}}$$
$$\text{Stay-time} = \frac{300 \text{ mrem}}{720 \text{ mrem/hr}} = \frac{1}{2.4} \text{ hr}$$
$$\text{Stay-time} = \frac{60 \text{ min}}{2.4} = 25 \text{ min.}$$

ANSWER: Stay-time = 25 min.

The MPE for past field operations has been set at 3.9 r/13 wks or 3.0 r/13 wks. It must be emphasized that dose rates in the r/hr and tens of r/hr ranges will not be uncommon. Work in such areas requires efficient planning and control of stay-times. The dosage control problem is made more critical because of the problem of removable contamination in the field.

In sample recovery operations, personnel leave the decontamination center in uncontaminated protective clothing and go into a contaminated zone performing their jobs. They will usually be working in a highly contaminated zone and then will go back to the decontamination center. The dose rate is no longer constant as in the laboratory situation above. The case is further complicated by the recovery party's carrying radioactive samples in addition to their wearing contaminated clothing. Dosage control calculation is no longer the simple use but rather the incremental use of the stay-time formula.



PROBLEM: Suppose a recovery party had to enter a 5 r/hr contaminated zone and recover three fallout collectors. 45 minutes is required to travel from the decontamination center to the edge of the contaminated zone, and then an additional 15 minutes is required to reach the site of the fallout collectors. An aerial survey indicates no hot spots along the route. The survey shows that the dose rate increases rather uniformly from 200 mr/hr to 5 r/hr. Six minutes will be required to recover the samples. What dose will the members of the recovery party receive?

SOLUTION: (a) Dose received in traveling into and out of the contaminated zone: The solution is similar to calculating average speed and distance traveled where the rate of exposure in r/hr is similar to speed in mi/hr and the accumulated dose is comparable to the number of miles traveled in a given time. The average dose rate is then $(\frac{0.2 + 5.0}{2})$ r/hr or 2.6 r/hr. Therefore, the dose during transit (15 min in and 15 min out) is approximated by (dose rate) x (time) or 2.6 r/hr x $1/2$ hr = 1.3 r.

(b) Dose received during recovery of sample in the 5 r/hr zone: The dose rate here is constant for the 6 minutes it takes to recover the samples and to place them in their shielded containers. The dose is then equal to (dose rate) x (time) or $(5 \text{ r/hr} \times \frac{6}{60} \text{ hr})$ or 0.5 r.

(c) Dose from contaminated clothing: There is no way to accurately calculate this exposure; but it may be estimated from the working habits of the recovery party and from past experience. Assuming a clothing contamination dose rate of 260 mr/hr produced at the time the recovery of the fallout collection was made and a total travel time of 1 hour back to the decontamination center, the dose from the clothing contamination would be $260 \text{ mr/hr} \times \frac{66}{60} \text{ hr}$ or approximately 0.3 r. When high clothing contamination is suspected, two sets of coveralls should be worn. The outer set must be removed as soon as practicable.

ANSWER: Total dose is then the sum of (a), (b), and (c) or $(1.3 + 0.5 + 0.3)$ or 2.1 r.

DOSE RATE AND DOSE CALCULATIONS FROM FISSION PRODUCTS

Fission-product decay follows a t^{-n} decay where n varies with time after detonation. A good working average is obtained by letting $n = 1.2$, giving a $t^{-1.2}$ decay. The graph, Fig. E-3 (Page 295) shows the $t^{-1.2}$ decay curve. The percent of initial activity in units of r/hr or curies is plotted against the time after detonation in any unit of time. The following illustrates use of this graph.

PROBLEM: Calculate the dose rate 7 days after detonation (D + 7) in a given location if the dose rate in that location was 200 r/hr 23 hours after detonation.

SOLUTION: Step 1: Take 200 r/hr as 100% activity with age of 1 day (time after detonation).

Step 2: Use the day as the unit of time and find the percent of initial activity remaining for 7 days. Read up to 7 on the vertical scale, move to the right to the intersection of the 7 day line on the $t^{-1.2}$ curve, drop down to horizontal scale and read the percent of remaining activity. The value will be 9.3%.

Step 3: Multiply 200 r/hr x 9.3% = 200 r/hr x .093
= 18.6 or 19 r/hr.

ANSWER: 19 r/hr is the dose rate at D + 7.

In the normal course of monitoring, dose rate readings are made at varying times after detonation. It is necessary to correlate the data to some common time unit. The common time-base used is the dose rate at 1 hour (H + 1) or 1 day (D + 1) after detonation. All monitoring survey results are eventually normalized to the H + 1 or the D + 1 value to give the H + 1 or the D + 1 dose rate. The following problem will illustrate the procedure.

PROBLEM: The fallout contamination dose rate measured on the forward main deck of a ship is 5.8 r/hr 15 hours after detonation. What was the dose rate 1 hour after detonation?

SOLUTION: Step 1: Since H + 1 is being used as the base time, then the dose rate at 1 hour will be 100% of the initial activity. The 5.8 r/hr then is some percent of initial activity remaining after 15 hours. Reading

the value of the percent of initial activity remaining after 15 hours and dividing it into the H + 15 dose rate will give the H + 1 dose rate. From the graph, the percent of initial activity remaining after 15 hours is equal to 3.9%.

$$\text{Step 2: H + 1 dose rate} = \frac{\text{H + 15 dose rate}}{\text{percent of activity remaining}} =$$

$$\frac{5.8 \text{ r/hr}}{3.9\%} = \frac{5.8 \text{ r/hr}}{0.039} = 150 \text{ r/hr.}$$

ANSWER: H + 1 dose rate = 150 r/hr.

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If the dose rate is normalized to D + 1 dose rate, the units of time after detonation will be days. A dose rate measured as 0.35 r/hr 4 days after detonation would represent 19% of initial activity remaining after 4 days. This would give a dose rate of  $\frac{0.35 \text{ r/hr}}{19\%} = 1.9 \text{ r/hr}$  at D + 1.

Appendix E also presents the  $t^{-1.2}$  decay in the form of two tables. Table E-1 allows the dose rate measured at any time to be used to predict the dose rate at any other time, while Table E-2 enables the accumulated dose at a location to be computed if the dose rate at a time after burst is known.

PROBLEM: If the fallout contamination dose rate at H + 10 is measured as 20 r/hr, what will the dose rate be at H + 72 hours?

SOLUTION: Step 1: From Table E-1, the factor corresponding to H + 10 is found to be 15.4. Multiply the H + 10 dose rate by this factor to find the H + 1 dose rate.  $20 \text{ r/hr} \times 15.4 = 308 \text{ r/hr}$  at H + 1.

Step 2: From Table E-1, the factor corresponding to H + 72 is found to be 155. The dose rate at H + 72 is the H + 1 dose rate divided by this factor or  $\frac{308 \text{ r/hr}}{155} = 1.97 \text{ r/hr}$ .

ANSWER: H + 72 dose rate = 2 r/hr.

**PROBLEM:** The dose rate in area A at H + 7 was found to be 6 r/hr. A man entered area A at H + 10 and departed at H + 20. What dose did the man receive?

**SOLUTION:** Step 1: From Table E-1, the H + 7 factor is found to be 10; thus the H + 1 dose rate is 6 r/hr x 10 or 60 r/hr.

Step 2: From Table E-2, the accumulated dose to H + 10 with a dose rate of 60 r/hr at H + 1 is found to be 492 r. At H + 20 the accumulated dose with a dose rate of 60 r/hr at H + 1 is found to be 516 r. Since the man was present from H + 10 to H + 20, the dose received is 516 r minus 492 r or 24 r.

**ANSWER:** Dose from H + 10 to H + 20 = 24 r.

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**PROBLEM:** Assume two ships are to be decontaminated by one decontamination team that has been ordered not to exceed a total dose of 3 r. It is estimated that two hours per ship will be required to perform the decontamination. If the dose rate on Ship A at H + 2 hours is 50 r/hr and on Ship B 5.7 r/hr at H + 6 (consider dose rate constant during decontamination) determine:

- a. Which ship shall be decontaminated first.
- b. At what H + time will decontamination commence.
- c. At what H + time will decontamination of the second ship start.
- d. At what H + time will decontamination of both ships be completed without exceeding the established dose of 3 r.

**SOLUTION:** Step 1: Since Ship A has the higher dose rate the major portion of the team's allotted dose will be expended in this effort. As a trial solution of the problem, assign a dose of 2 r to be received on Ship A. This requires a dose rate of 1 r/hr on the ship.

- Step 2: Using Appendix E, Table E-1, find the H + 1 dose rate if the H + 2 dose rate is 50 r/hr. H + 2 factor is 2.28. Therefore the H + 1 dose rate is  $50 \text{ r/hr} \times 2.28 = 114 \text{ r/hr}$ .
- Step 3: If the dose rate at the start of decontamination must be 1 r/hr, then the H + 1 dose rate must be reduced by a factor of  $\frac{114 \text{ r/hr}}{1 \text{ r/hr}} = 114$ . From Table E-1 find the time corresponding to the factor of 114. This time is about H + 54 hr.
- Step 4: Since 2 r has been expended on Ship A, 1 r may be received decontaminating Ship B. The dose rate for a 1 r dose in 2 hr would be  $\frac{1 \text{ r}}{2 \text{ hr}} = .5 \text{ r/hr}$ . Again, using Table E-1, the H + 6 dose rate of 5.7 r/hr gives an H + 1 dose rate of 47.5 r/hr. If 47.5 r/hr is to be reduced to 0.5 r/hr, the factor is  $\frac{47.5 \text{ r/hr}}{.5 \text{ r/hr}} = 95$ . The time corresponding to 95 is about H + 46 hours.

- ANSWER:
- Ship B will be decontaminated first.
  - Decontamination of Ship B will commence at about H + 46
  - Ship A will be decontaminated second, starting at about H + 54.
  - Decontamination of both ships will be completed by H + 56 with a dose of 1 r expended on Ship B and 2 r expended on Ship A.

Obviously the above solution to the problem is not unique. The time of start of decontamination may be adjusted by selecting other distribution of dose to be received on each ship.

## RULES OF THUMB FOR FISSION-PRODUCT GAMMA DOSE AND DOSE RATE ESTIMATES

Decay tables and graphs will not always be available for calculating dose and dose rate values from fission-product contamination. There are five "rules of thumb" that may be used to approximate the dose and dose rates. These rules of thumb enable a person to make rapid, reasonably accurate mental calculations of the radiological situation at any future time. To use these rules, two things must be known:

- ① Average DOSE RATE in area under consideration.
- ② TIME that has elapsed between the time of the dose rate reading and the time of the burst.



DOUBLE THE TIME SINCE DETONATION, DOSE RATE IS DOWN TO  $1/2$ . SAY IT ANOTHER WAY: THE APPARENT HALF-LIFE IS ABOUT EQUAL TO THE AGE.

**PROBLEM:** The dose rate in a certain area is 80 r/hr two hours after the explosion. What will the dose rate in that same area be four hours after the explosion?

**SOLUTION:** Time since explosion:  $H + 2$  hours  
Present dose rate ( $H + 2$ ): 80 r/hr  
 $H + 4$  dose rate =  $1/2 \times 80$  r/hr = 40 r/hr.

**ANSWER** Dose rate at  $H + 4$  is 40 r/hr.

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**PROBLEM:** Under the same original conditions as in the preceding problem, when will this dose rate have decayed to 20 r/hr?

**SOLUTION:**  $H + 2$  dose rate = 80 r/hr  
 $H + 4$  dose rate = 40 r/hr  
 $H + 8 = 20$  r/hr

**ANSWER** Therefore, the dose rate will be 20 r/hr at  $H + 8$ .

Nuclear weapon debris or fission-product contamination is a mixture of almost 200 radionuclides, each with its own specific half-life. The APPARENT HALF-LIFE of fission-product contamination is the time it takes a quantity of fission-product material to decay to one-half its original amount. The greater the age of the fission products, the greater the APPARENT HALF-LIFE. The APPARENT HALF-LIFE of fission-product material is approximated by the age of the material. The apparent half-life at H + 8 hours is 8 hours, at D + 5 days is 5 days.



AT SEVEN TIMES THE PRESENT AGE, THE RADIATION LEVEL WILL BE 1/10 THE PRESENT DOSE RATE. FROM AGE 1 DAY TO AGE 7 DAYS, THE DOSE RATE FALLS TO 1/10; AT AGE 49 DAYS, IT FALLS TO 1/100.

**EXAMPLE:** If the dose rate is 36 r/hr at 1 day after detonation, then the dose rate will be 3.6 r/hr at 7 days and 0.36 r/hr at 49 days.



FOR SHORT-TIME EXPOSURE (LESS THAN ONE APPARENT HALF-LIFE), ASSUME DOSE RATE CONSTANT.

**PROBLEM:** A group of men in a certain area have received a dose of 100 r. This dose was accumulated from the time of the burst until two hours later (dosimeter reading). At H + 2, a monitor reports a dose rate in their area of 50 r/hr. If the men stay in the area during the next hour, what will be their approximate dose at the end of that time?

**SOLUTION:** Dose to H + 2: 100 r  
Dose rate at H + 2: 50 r/hr

Assume that this dose rate remains constant during the hour ( less than the apparent half-life of 2 hours).

**ANSWER** Dose from H + 2 to H + 3:  $50 \times 1 = 50$  r  
Total dose to H + 3:  $50 + 100 = 150$  r.



The dose computed by Thumb Rule 3 introduces some error into the answer because the dose rate was assumed to remain constant, while actually it was decreasing. This error tends to give us a greater safety margin in determining time of stay in an area than would a more accurate means of arriving at the answer. The third thumb rule permits more accurate dose computations for longer periods of time.



GAMMA DOSE TO INFINITE TIME EQUALS  $5 \times R/HR$   
AT PRESENT  $\times$  HOURS SINCE DETONATION - OR  $5IT$ .

**PROBLEM:** A group of men in a certain area find that they have accumulated a gamma dose of 50 r in the first two hours following a burst. A dose rate reading at that time indicates a dose rate of 25 r/hr. What will be the total dose that the men would accumulate if they remained in that area indefinitely?

**SOLUTION:** Dose to H + 2 (dosimeter): 50 r

Dose from H + 2 to infinite  
time =  $5 \times I \times T$  or  $5 \times 25 \times 2 = \underline{250 \text{ r}}$

**ANSWER:** Total dose: 300 r

Thumb Rule 4 calculates dose to infinite time, a situation which could not possibly exist. In practical application, this rule may be applied with reasonable accuracy to any period of time greater than two weeks. A major portion of the total dose is accumulated during this period. Thumb Rule 5 estimates the dose for one APPARENT HALF-LIFE.



DOSE ACCUMULATED IN ONE APPARENT HALF-LIFE  
EQUALS  $1/10$  OF  $5IT$ .

**PROBLEM:** The dose rate in a certain area at  $H + 5$  is 50 r/hr. What dose will be received in the next half-life period?

**SOLUTION:** Dose from  $H + 5$  to infinite time  
 $(5IT) = 5 \times 50 \text{ r/hr} \times 5 \text{ hr} = 1250 \text{ r}$

Next apparent half-life is 5 hr.

Dose from  $H + 5$  to  $H + 10$ :

**ANSWER:**  $\frac{5IT}{10} = \frac{1250}{10} = 125 \text{ r}$

## THE RULES OF THUMB



DOUBLE THE TIME, DOSE RATE  
IS  $1/2$ ; THE APPARENT HALF-LIFE  
IS ABOUT EQUAL TO THE AGE

DOSE RATE



AT SEVEN TIMES THE PRESENT AGE,  
THE RADIATION LEVEL WILL BE  $1/10$   
THE PRESENT RADIATION LEVEL

DOSE RATE



FOR SHORT-TIME EXPOSURE, ASSUME  
DOSE RATE CONSTANT

DOSE



GAMMA DOSE TO INFINITY EQUALS  
 $5 \times$  PRESENT DOSE RATE  $\times$  TIME AFTER  
DETONATION, OR 5IT

DOSE



DOSE IN 1 (ONE) APPARENT HALF-LIFE  
IS  $1/10$  DOSE TO INFINITY, OR  $1/10$  (5IT)

DOSE

# SUMMARY

**MINIMIZE PERSONNEL EXPOSURE!    ALWAYS USE COMMON SENSE!**

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These themes are a vital part of Chapter 2, just as they constituted a vital part of Chapter 1.

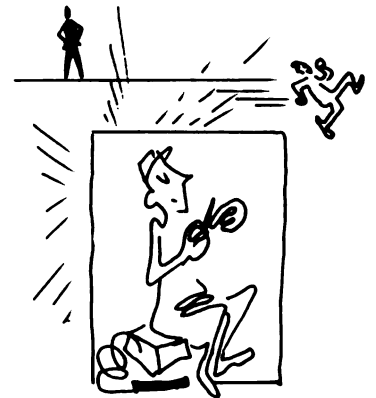
Chapter 2 has emphasized the importance of understanding the major problems involved in radiological safety. The monitor must understand the use of equipment and facilities as he must understand the necessity of following those radiological safety procedures which are established for radiation and contamination control.



A thorough familiarity with terms is important. Maximum Permissible Exposure, Maximum Permissible Concentration, Maximum Permissible Limit, and Maximum Permissible Dose were explained in detail.

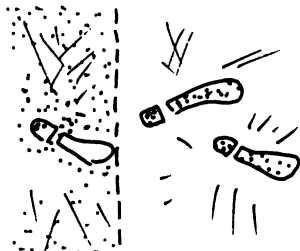


External radiation and internal contamination control problems were discussed, and safety measures for both types of problems were shown to be different. Radiation dosage from external radiation can be controlled by any one or a combination of: time, distance, shielding, and radioactive decay. Internal contamination can be controlled by protection from inhalation, ingestion, and absorption of radioactive materials into the body.

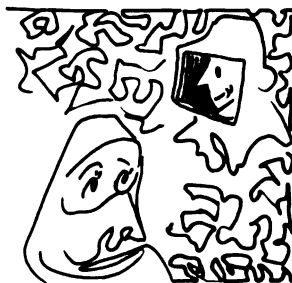




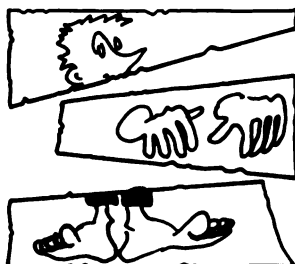
This Chapter emphasized that radioactive material within the body is very serious because biological elimination cannot be hastened. Radioactive materials can enter the body by inhalation, ingestion, and absorption. Limits have been established for the amount of radioactive material that may be accumulated within the body (permissible body burden).



Necessity of contamination control was stressed. The important factor is determining the source of the contamination. SPREADING contamination and CONTROLLING contamination are both easy to do.



Chapter 2 emphasized the importance of proper protective clothing. If excessive contamination is allowed to remain on the body surface, significant radiation burns may be produced. Continued emphasis must be placed on the necessity of applying proper technical information to establish practical safety precautions. Always use common sense!



Illustrated examples of personnel decontamination centers have been given. This Chapter listed methods of partial and complete body decontamination.



Reasonably safe working levels have been established. Types of handling devices were illustrated and their functions described. The reader has been cautioned that safe working levels must not be exceeded.

Chapter 2 explained some of the ways contamination may be found: lying loose, absorbed in porous materials, bonded to a material through oil or grease. This Chapter explained methods employed in decontaminating surfaces, equipment, shipboard, and clothing. Zone control, restricting the contaminated area to minimize spreading contaminated material, is extremely important.



Unique problems are presented by shipboard circumstances. For instance, the cooling system of a ship, though vital to efficient operation, can be responsible for spreading contaminated material throughout the ship.



Airborne contamination is also an important shipboard problem. Tracking and spreading contaminated material on board ship presents a serious problem because of the confined quarters.



Disposing of waste material and the storage and transportation of radioactive material were discussed. Particular emphasis was placed on the necessity of control.



Health Physics computations were presented. This Chapter listed "rules of thumb" which have been developed because times may occur when the specific formulae may not be immediately available.



Radiological safety is the responsibility of every individual. Rad-safe principles and procedures presented in Chapter 2 will enable the monitor to know . . . .

**where** the problem is,

**what** should be done about it,

he must further know

**HOW** to monitor radiation



# **CHAPTER 3**

## **MONITORING**

Radiation monitoring is the systematic determination of the nature and extent of radiation and contamination problems. Radiation monitoring is the process of using radiac (monitoring) instruments to ASSESS the radiological situation in order to effectively DELINEATE and CONTROL the radiation exposure and the radioactive contamination of personnel. The radiation monitoring survey is one of the most important jobs of the monitor, for the application of radiological countermeasures starts with the assessment of the radiological situation. The monitor must know how to perform a gross monitoring survey to define the order of magnitude of the situation. The monitor must also know how to perform detailed monitoring surveys to pinpoint the problems of hot spots, removable contamination, airborne contamination, personnel contamination, etc.

# ASSESSMENT OF THE RADIOLOGICAL SITUATION

Assessment of a radiological situation requires the monitor to measure the radiation and contamination levels so that he can (1) evaluate the radiological problem and then (2) institute rad-safe controls.

To assess the radiological situation, the monitor must measure and determine:

- ① The types and dose rates of radiations present.
- ② The amount of fixed and removable contamination.
- ③ The liquid and aerosol contamination levels.

The monitor controls the external radiation exposure, the internal contamination of personnel, and the spread of contamination by:

- ① Limiting the time spent in the radiation area.
- ② Application of rad-safe procedures to control the fixed and removable contamination.
- ③ Use of shielding, remote handling devices, controlled atmospheres, and personnel-protective equipment.

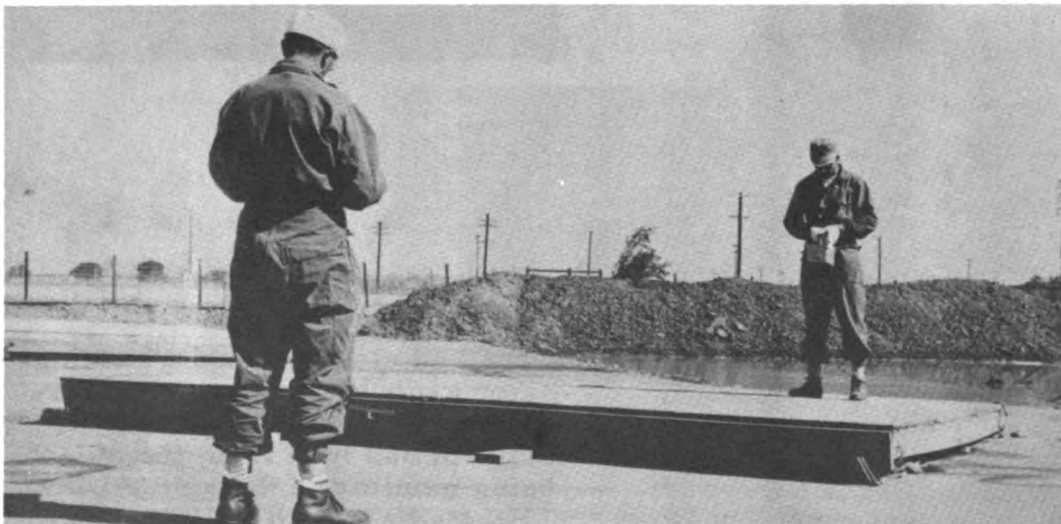


**The monitor must always record:**

- ① The object or area monitored.**
- ② The location of the object or area monitored.**
- ③ The types and dose rates of radiation.**
- ④ The amount of fixed and removable contamination.**
- ⑤ The amount of liquid and aerosol contamination.**
- ⑥ The distance of the radiac from the object monitored.**
- ⑦ The type of monitoring instrument used.**
- ⑧ The time and the date the measurement was made.**
- ⑨ The identification of the monitor.**

**The monitor's identification is necessary for two important reasons: first, to certify the data as an accurate record of the radiological situation and second, to enable correlation of monitoring data if further information is necessary.**

**A uniform monitoring procedure must be followed by all monitors. Uniformity of monitoring data is of prime importance in evaluating a radiological situation, especially when one considers that future operations are based on the data obtained from previous monitoring surveys.**

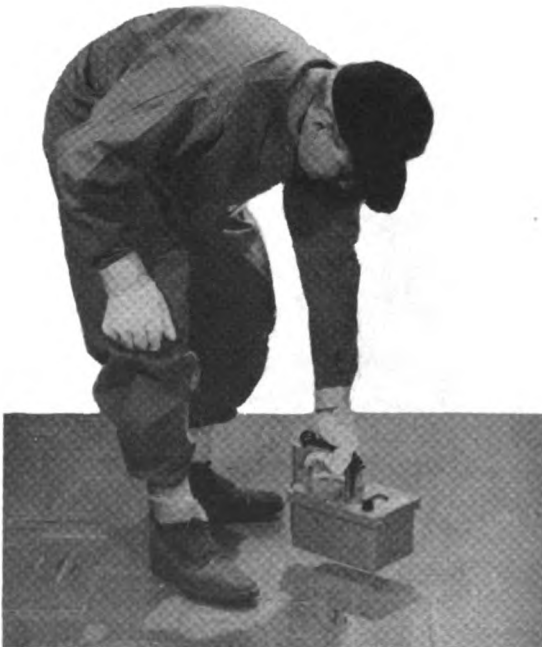


# BASIC MEASUREMENT TECHNIQUES

Uniformity of radiation-measurement techniques is a fundamental necessity in monitoring. Data must be standardized. Since a radiac held in different positions or at different distances from a radiation source will give different readings, three basic types of measurement techniques are recommended.

## ▶ **WAIST-HIGH**

Open and closed-window (shielded or unshielded to differentiate between the soft and hard radiations) readings are taken with the sensitive portion of the instrument held at waist height, about 3 ft above the surface being monitored.



## ▶ **NEAR-CONTACT**

Open and closed-window readings are taken with the sensitive portion of the instrument at a distance of one inch from the object being monitored. NEVER ALLOW THE MONITORING INSTRUMENT TO TOUCH CONTAMINATED GROUND OR OBJECTS.

## REMOVABLE CONTAMINATION

An estimate of the amount of removable contamination may be made by a wipe or smear test. A wipe sample is made by rubbing a clean piece of absorbent paper lightly over the surface in question. (Whatman #1 filter paper, toilet tissue, etc., may be used.) The wipe should cover an area of about 12 square inches. The wipe should be taken with constant pressure on the paper. A detailed discussion of wipe-testing is presented on Page 164.

The amount of contamination picked up by a wipe sample is roughly 10% of the removable surface contamination but varies widely depending on the monitor's wipe technique, type of contamination, and surface condition of the tested area. Nevertheless, the wipe survey is a good operational procedure for estimating the amount of removable activity and is a common practice in all laboratories using radioactive materials.



# RADIATION MONITORING INSTRUMENTS -- RADIACS



Radiation monitoring instruments must be used to assess the radiological situation. There is no single radiac which can measure all dose rate levels and types of radiation. The monitor must be able to choose the proper instruments for various monitoring situations. If the monitor does not have advance information regarding what types and levels of radiation will be present in a given situation, he should go prepared to measure all the various conditions that could possibly exist.

An efficient monitor should know the problems associated with various types of radiological incidents. Experience, education, and training provide the knowledge which enables the monitor to evaluate various radiological situations.

For example, in a field operation the radioactive material of interest will probably be fission products which emit beta particles and gamma rays. Therefore, the monitor would take a gamma radiac and also a beta radiac. Near ground zero, or in the fallout zone, the intensities of the radiations would be moderate to very high. A trained monitor would choose two radiacs which would cover the ranges from medium to high-level dose rates. A gamma radiac is used first because the primary radiological hazard is from the penetrating gamma radiation. If, by some chance, only the high-explosive component of the nuclear weapon had detonated, the monitor would choose instruments for monitoring low-level beta-gamma and alpha contamination.

## **RULES AND GUIDELINES FOR THE USE OF INSTRUMENTS**

- 1** Select the radiac that will measure the type of radiation known to be present.
- 2** Determine whether or not the radiac will measure the dose rate of the radiation in question. Take more than one radiac, if necessary, to give full coverage of ranges.
- 3** Use a range setting that allows the radiation level to be read on the upper two-thirds of the meter dial.
- 4** Check the radiac for proper operation before leaving the issue room. A defective or inoperative instrument is worthless.
- 5** Handle radiacs with care -- they are delicate electronic instruments.
- 6** Protect the instrument from contamination. Do not allow instruments to come into contact with contaminated surfaces. Cover with plastic sheeting, as shown in the photograph on the opposite page.
- 7** Check the zero set and full scale adjustment every 10 or 15 minutes during a prolonged monitoring survey.
- 8** Watch for "HOT SPOTS." Hot spots are those areas which are 10 or more times greater than the average intensity. Hot spots are produced by a concentration of the contamination.
- 9** For gross monitoring surveys, read only to the closest scale division and record no more than two significant figures. For example, on an AN/PDR-27, record 150 mr/hr, not 152 mr/hr. If the meter oscillates between two or three scale divisions -- 17, 18, 19 r/hr, record the average, 18 r/hr. Radiac instruments are designed for  $\pm 20\%$  accuracy. Do not waste time trying to read radiacs to  $\pm 1\%$  accuracy.
- 10** In detailed monitoring surveys, proceed slowly and carefully. Accuracy is more important than speed. Whenever a reading is being taken (especially in low-level monitoring), stop and hold the instrument steady for enough time to allow the meter to reach maximum deflection. When switching from one scale to another, allow time for the meter reading to stabilize.



Rules for the use of radiacs will become automatic in the actions of a good monitor. He will do these things instinctively every time he picks up a radia. The following radia Classification Chart is presented to aid the monitor in the selection of the proper monitoring instrument. The theory of radia operation is presented in Volume III, Chapter 3. Detailed operating procedures for the instruments listed below are presented in Appendix B of this Volume.

| RADIAC CLASSIFICATION CHART               |                                               |                                                  |                |       |      |                 |     |      |
|-------------------------------------------|-----------------------------------------------|--------------------------------------------------|----------------|-------|------|-----------------|-----|------|
| TYPE OF RADIATION                         | RADIAC                                        | RANGE                                            | APPLICABLE FOR |       |      |                 |     |      |
|                                           |                                               |                                                  | SURVEY         |       |      | RADIATION LEVEL |     |      |
|                                           |                                               |                                                  | Pers           | Equip | Area | Low             | Med | High |
| $\beta$ - $\gamma$                        | AN/PDR-27 series                              | 0-5 mr/hr $\beta$ - $\gamma$                     | x              | x     |      | x               |     |      |
|                                           |                                               | 0-500 mr/hr $\gamma$                             |                | x     | x    | x               | x   |      |
|                                           | SIDE WINDOW G-M COUNTER, Eberline Model E112B | 0-20 mr/hr $\beta$ - $\gamma$                    | x              | x     | x    | x               |     |      |
|                                           | CUTIE PIE (El-Tronics) Model CP-3DM           | 0-100 rad/hr                                     | x              | x     | x    | x               | x   |      |
| $\gamma$                                  | AN/PDR-39 (TIB)                               | 0-50 r/hr                                        |                | x     | x    | x               | x   |      |
|                                           | AN/PDR-18 series                              | 0-500 r/hr                                       |                | x     | x    |                 | x   | x    |
| $\alpha$                                  | AN/PDR-10 series                              | 0-10K d/m/150cm <sup>2</sup>                     | x              | x     |      | x               |     |      |
|                                           | Eberline Proportional Counter, PAC-3G         | 0-100K c/m/60cm <sup>2</sup>                     | x              | x     | x    | x               | x   |      |
| $\alpha$ - $\beta$ - $\gamma$             | JUNO Survey Meter (Technical Assoc.)          | 0-10 <sup>7</sup> d/m/80cm <sup>2</sup> $\alpha$ | x              | x     | x    |                 | x   | x    |
|                                           |                                               | 0-5 r/hr $\beta$ - $\gamma$                      |                | x     | x    | x               | x   |      |
| FAST NEUTRON                              | AN/PDR-47 (Interim Model)                     | 0-500 mrad/hr                                    |                |       | x    | x               | x   |      |
| FAST AND SLOW NEUTRON                     | AN/PDR-49 (Interim Model)                     | 25,000 n/cm <sup>2</sup> /sec                    |                |       | x    | x               |     |      |
| $\beta$ - $\gamma$ FAST AND SLOW NEUTRONS | Film Badges and other Dosimeters              | Variable -- dependant upon equipment             | x              | x     | x    | x               | x   | x    |

In addition to the proper instruments, the monitor must be equipped with other tools to carry out his mission successfully. The following is a list of the additional material that may be required.

- 1 Personnel dosimeters -- such as a film badge to record the monitor's radiation exposure and self-reading pocket dosimeters so that he may continually check his own dose (Volume III, Chapter 3, presents information on the response characteristics and other features of photographic and pocket dosimeters).
- 2 Protective clothing -- to prevent contamination of his person.
- 3 Mask -- if the area has airborne contamination in excess of the MPC.
- 4 Notebook or paper -- to record the data collected.
- 5 Communication equipment.
- 6 Transportation as required.
- 7 Time piece (watch).
- 8 A diagram, map, or knowledge of the area to be covered.
- 9 Special sampling gear for air, water, or wipe samples.
- 10 Delineation equipment -- signs, markers, rope, etc.

# RADIOLOGICAL SITUATIONS

Radiological situations may be classified into the four following categories:

|   | Situation                                 | Source                                                                            |
|---|-------------------------------------------|-----------------------------------------------------------------------------------|
| A | RADIATION CONTROL                         | RADIATING MACHINES AND SEALED SOURCES                                             |
| B | MINOR RADIATION AND CONTAMINATION CONTROL | LESS THAN 10 MC $\beta$ - $\gamma$ EMITTERS                                       |
| C | MAJOR RADIATION AND CONTAMINATION CONTROL | MORE THAN 100 MC $\beta$ - $\gamma$ EMITTERS                                      |
| D | CONTAMINATION CONTROL                     | ANY $\alpha$ EMITTERS AND LESS THAN 10 MC PER YD <sup>2</sup> OF $\beta$ EMITTERS |

Individual actions may differ in each of the above situations; however, the objective always remains the same: PREVENT HARMFUL BIOLOGICAL EFFECTS FROM IONIZING RADIATIONS!

## **A RADIATING MACHINES AND SEALED SOURCES**

High dose rates may be present in the vicinity of large sealed sources such as those used in a calibration range and for radiography. High dose rates may be present around machines producing ionizing radiations, such as X-ray machines, Van de Graaffs, and cyclotrons.

Radiation monitoring consists of measuring and evaluating the dose rates associated with the various operations. It is also important to measure the type, quantity, and energy of the various ionizing particles produced by high energy accelerators in order to properly evaluate the rem dose rate. Radiation warning signs are posted, and stay-time limits are established for radiation areas. It is important to monitor over, under, and around the immediate radiation area because personnel in adjacent areas may be in a radiation field produced by radiation beams coming through the floor, walls, etc. Contamination-control measures are not required for radiation-producing machines and SEALED sources. If the source container breaks, contamination-control measures will be required. Emergency procedures for such accidents are listed in Appendix F of this Volume.

## **B LESS THAN 10 MILLICURIES OF BETA-GAMMA EMITTERS**

In areas where low levels of radioactive materials are present (research laboratories, radium-dial painting shops, sample-handling rooms, etc.), radioactive contamination may be present without any appreciable radiation dose rate. The problem is to locate and delineate the areas of contamination in order to control the spread of the contamination. This low-level beta-gamma contamination presents a minor biological problem. It may become a technical problem if it is allowed to spread to areas that must remain free of contamination, such as counting rooms or bio-assay laboratories. Internal contamination should always be minimized wherever possible. Protective clothing, personnel monitoring, rad-safe procedures, and decontamination are used to control contamination.

Low-level contamination is insidious because it may easily be overlooked by the monitor. The fact that low-level contamination can go unrecorded on the dosimetric devices allows time for contamination to spread to clean areas or to be transferred into the body.

## **C MORE THAN 100 MILLICURIES OF BETA-GAMMA EMITTERS**

High radiation intensities and contamination levels exist in early-time fallout zones and nuclear accidents. The radiological monitor must be able to measure and differentiate between the gamma radiation dose rate and the radioactive contamination level. Adequate radiological counter-measures will depend upon these measurements. The radiation dose rate will determine the stay-time of personnel while the contamination level will determine the personnel-protective equipment and rad-safe procedures required for work in the area. Frequent monitoring surveys may be necessary in heavily contaminated areas to minimize personnel exposures and internal contamination and to maintain zone control of the contamination.

## **D ANY ALPHA EMITTERS AND LESS THAN 10 MILLICURIES PER YD<sup>2</sup> OF BETA EMITTERS**

Alpha emitters present a special radiological problem. The short range of alpha particles makes monitoring difficult and tedious. The low MPC's for alpha emitters make detailed monitoring procedures necessary. Alpha contamination requires strict and immediate delineation and control. Protective clothing is mandatory, and continuous monitoring of personnel and work areas may be necessary. Beta-emitting isotopes also present a contamination problem. The low-energy beta emitters, such as  $C^{14}$  and  $H^3$ , require special monitoring equipment and procedures. These low-energy beta particles must be monitored with thin window (approximately  $1 \text{ mg/cm}^2$ ) ionization chambers or geiger tubes.  $Sr^{90}$ , a low-energy beta emitter, is easily monitored because of the high-energy beta particle emitted by its  $Y^{90}$  daughter.  $Sr^{90}$  must be carefully controlled because of its low MPC.

# **TYPES OF MONITORING SURVEYS**

The actual monitoring methods to be used in assessing a radiological situation will depend on such factors as time available, extent and amount of contamination, established MPE's and MPC's, type of area or facility, availability of monitoring teams and equipment, etc. However, it is possible to describe two basic monitoring methods that are used to gather data for the evaluation of a radiological situation.

## **1 THE RAPID OR GROSS SURVEY**

The rapid or gross survey gives a quick, over-all evaluation of the radiological situation. This type of survey emphasizes rapid dose rate measurements based on a minimum number of readings. The readings may be taken either at designated points or at designated radiation levels. GAMMA RADIATION MEASUREMENTS SHOULD BE MADE BY THE WAIST-HIGH TECHNIQUE TO GIVE AN ORDER-OF-MAGNITUDE ESTIMATE OF THE RADIOLOGICAL SITUATION. A subsequent plan of action is based on this estimate. Near-contact monitoring is used in the gross survey of alpha and beta emitters.

## **2 THE DETAILED SURVEY**

The detailed survey is a monitoring survey performed to provide additional specific data (such as amount of removable contamination; food, water, and aerosol contamination; complete radiation level plot, etc.) describing the complete radiological situation. RADIATION MEASUREMENTS SHOULD BE MADE BY BOTH THE WAIST-HIGH AND NEAR-CONTACT METHODS. The detailed survey is a continuation of the gross survey.

# GROSS MONITORING SURVEY

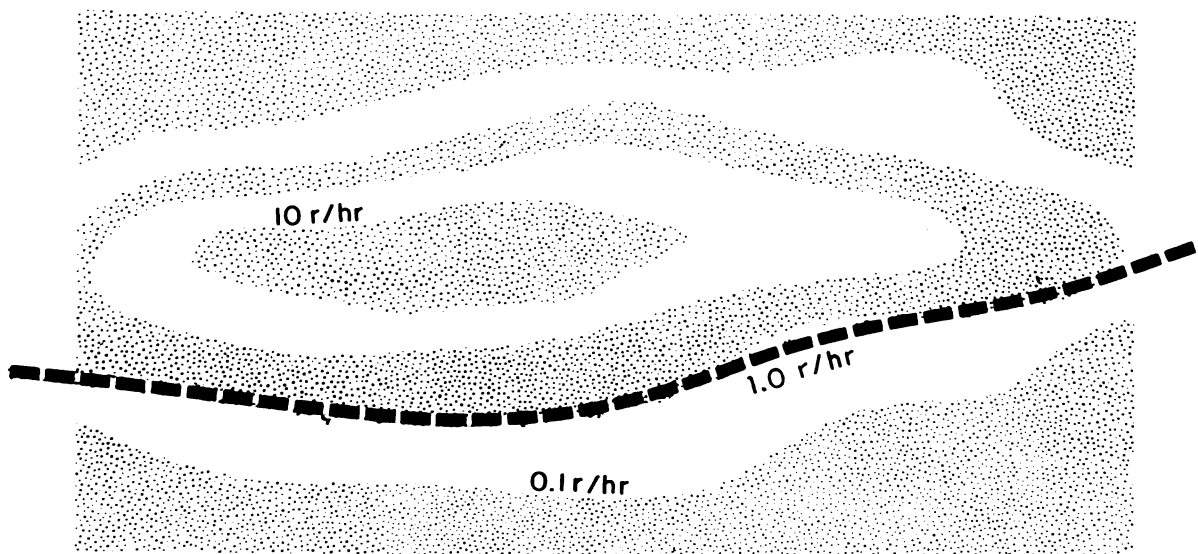
Gross monitoring survey methods for the assessment of the general radiological situation for land, sea, and industrial areas follow.

## LAND AREAS

A gross survey of a land area may be made by monitoring along a pre-designated dose rate contour (the constant-reading method) or by monitoring predesignated points or dose rates (the in-and-out method).

### ① CONSTANT-READING METHOD

The constant-reading method requires the monitoring team to penetrate into the area until it reaches a location which has the designated dose rate. The monitoring team then follows along a line determined by measurements having this specific dose rate. At suitable intervals the team reports and records its location. The following figure illustrates the constant-reading survey, showing the contour of the designated dose rate. This method is best suited to large areas where buildings, rough terrain, or other obstacles will not prevent or hinder the survey. In general, this type of survey may be accomplished at a rapid rate. However, this procedure exposes the monitoring teams to a given dose rate for a long period of time. Therefore, this method should be used where the dose rates are low enough to allow the monitoring team to complete the survey within the established dosage limits.

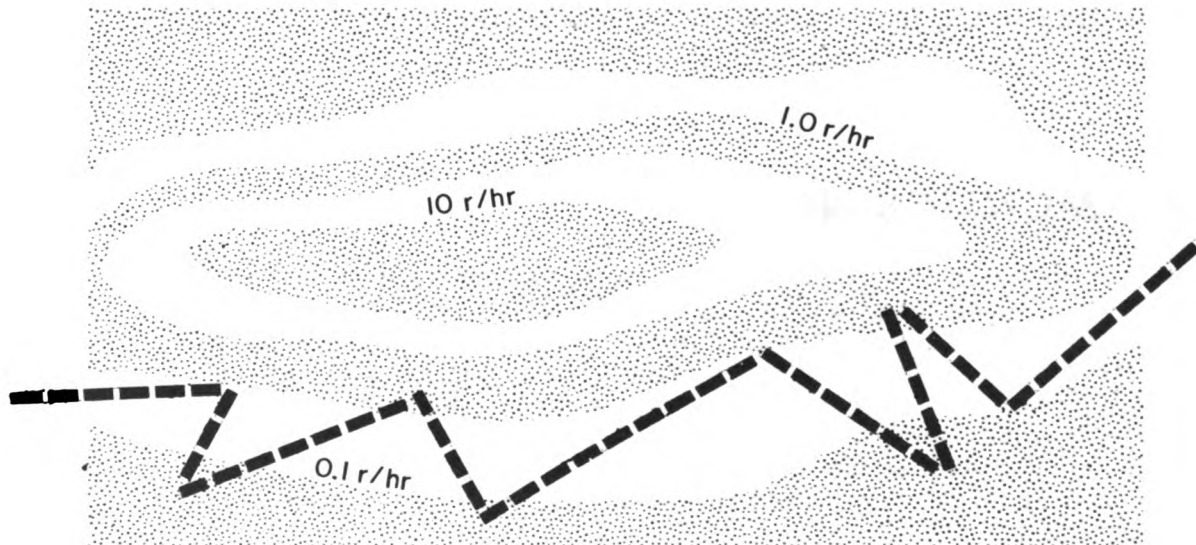




## ② IN-AND-OUT METHOD

If the area to be monitored is more highly contaminated and if the allowable exposure does not permit extended stay-time, the in-and-out survey method should be used. The monitoring team proceeds inward until it reaches the predesignated dose rate. At this point, the team posts markers and records and reports the location. The monitoring team then leaves the area by a DIFFERENT ROUTE, taking measurements and marking the area. The team circles its sector, repeating the penetration and withdrawal (in-and-out) until the sector has been monitored. (See the illustration below.) Compared to the constant-reading method, the in-and-out type of monitoring should reduce the radiation exposure of the monitoring team.

The in-and-out survey can be successfully accomplished by a two-man monitoring team operating in a light vehicle such as a jeep. The monitor, holding the radiac over the side of the vehicle, measures and records the radiation dose rate while the vehicle is in motion. The driver proceeds along a predesignated route and functions as a radio operator by relaying the monitoring data to the rad-safe center as the measurements are made.



## **AERIAL SURVEY**

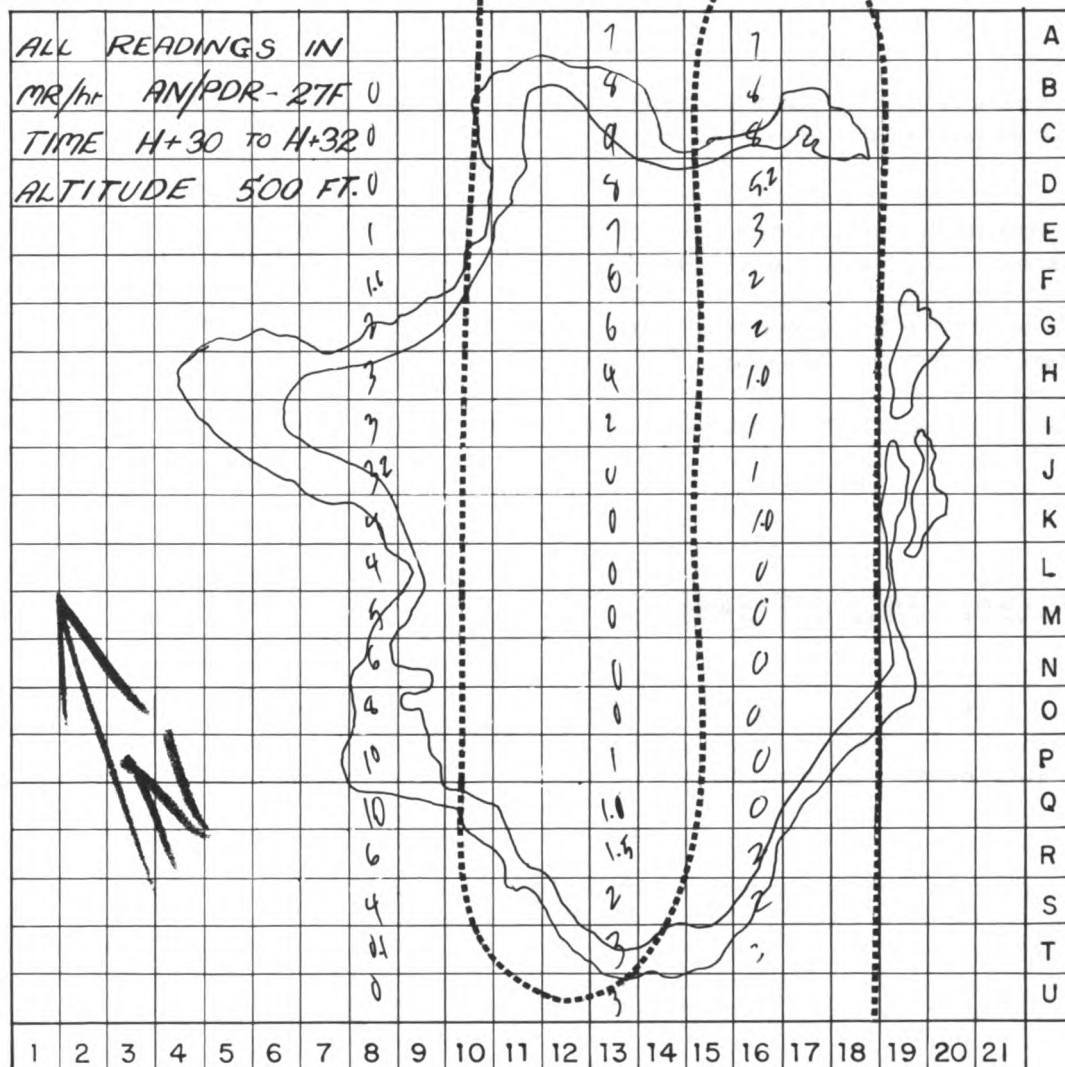
One of the most rapid methods of estimating the extent of a radiological situation is by means of an aerial survey using low-speed aircraft. Helicopters or fixed-wing aircraft flying at a constant height, 50 to several hundred feet, may be used. Gamma rays have a long range in air, and standard radiacs can be used to measure the radiation level. Figure E-2 in Appendix E is a graph relating the radiation dose rate measured at various heights to the radiation dose rate 1 foot above the surface for contaminated areas of various diameters. By knowing the height above ground and estimating the size of the contaminated area, the radiation dose rate observed in the aircraft may be corrected to indicate the dose rate at 1 foot above the surface.

Caution should be taken to prevent contamination of the aircraft by a contaminated cloud, since this contamination will affect the radiation measurements observed in the aircraft. If the aircraft becomes contaminated, the radiation dose rate attributed to this contamination must be subtracted from the total radiation dose rate before the ground estimate can be made.

The figure on the opposite page is an aerial survey of the Bikini Lagoon following a nuclear weapon test detonation. This survey was completed in less than 2 hours, using an AN/PDR-27F radiac in a Navy P2V aircraft flying at 170 knots at 500 ft. (The readings shown were measured in the plane and were not corrected to surface readings.)

## **OCEAN MONITORING**

Monitoring contaminated ocean areas can be carried out in the same manner as land-area monitoring. A vehicle capable of rapid movement (a destroyer or low-speed aircraft) is required to traverse the contaminated area. The area can be marked, if necessary, by the use of dyes or buoys. The contamination level of the water drops rapidly due to decay and to the settling of the radioactive materials. The amount of contamination in the water can be estimated by monitoring the radiation level at fixed points on the ship (bridge wing, bow, water line, etc.).



## INDUSTRIAL AREAS

The preceding monitoring procedures apply primarily to field tests and nuclear accidents. The principles involved in an industrial or laboratory monitoring survey are very similar, although generally on a smaller scale. Most experienced monitoring personnel will determine what radioisotope is present, its quantity, and general location before monitoring. When a monitoring survey is being made, a general area reading is taken (rapid survey), followed by a detailed monitoring survey. The monitor should always look several steps ahead to consider the potential spread of contamination from experimental set-ups or operating procedures. THIS PRECAUTION CANNOT BE OVER-EMPHASIZED.

# DETAILED MONITORING SURVEY

These surveys are performed to assess all of the parameters of a radiological situation and consist of:

- ▶ ① Monitoring all accessible locations in the radiation zone (radiation monitoring).
- ▶ ② Measuring the fixed and removable contamination (contamination monitoring).
- ▶ ③ Collecting aerosol and liquid samples as necessary.

## RADIATION MONITORING

The types of radiation and the dose rates present in an area of interest are determined. Radiation monitoring may be classified into three types: gamma, beta, and neutron.

The basic rules and procedures for radiation monitoring are:

- ① Select the proper radiac and rad-safe equipment.
- ② Check the radiac for proper operation.
- ③ Measure the AVERAGE RADIATION DOSE RATE in locations of interest.
- ④ Locate and measure the radiation dose rates from "hot spots."
- ⑤ Record the readings and delineate the radiation area.

Each type of radiation monitoring requires special techniques, depending upon the characteristics of the radiation in question.

## **GAMMA ( $\gamma$ ) MONITORING SURVEY**



The monitor should always turn on the radiac instruments before entering a radiation area. This is very important when the radiac has a G-M tube as the radiation-sensitive element. A G-M tube will saturate in a high radiation field and will indicate dose rates lower than are actually present. Ionization chamber and scintillation-type radiacs will go off scale if they are in a radiation field greater than their highest range. If a monitor must begin his survey in a radiation field, it is important that he use an ion chamber or a scintillation-type radiac in making the first measurement of the radiation dose rate.

Local radiation dose rates that are greater than 10 times the average radiation intensity are called "hot spots." These hot spots are caused by concentration of the radioactive contamination, and they may be located by following the increase of radiation dose rate along a path from a fixed starting point.

Large masses of material such as vehicles, buildings, and rises in land surface may act as a shield for  $\gamma$  radiations. The monitor should use caution in approaching sources of radiation that may be behind such masses. Many times the monitor will read moderate dose rates created by radiations penetrating shielding materials or by radiations scattered around a shielding mass. By moving only a slight distance, he will suddenly find a large increase in the radiation dose rate because he is then directly exposed to the radiation source.

The  $\gamma$  radiation dose rates are recorded in the units of roentgen per hour (r/hr) or its sub-multiple (mr/hr). The unit rad/hr is sometimes used, but generally the monitor records the type of radiac used and then reports all measurements in the unit indicated on the meter face of the radiac.

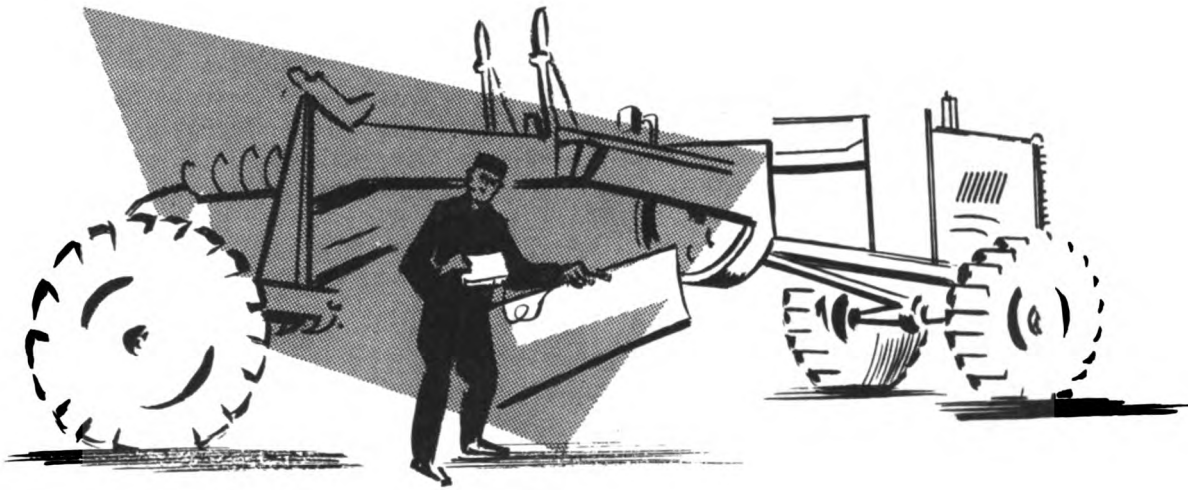
# **$\beta$ BETA ( $\beta$ ) MONITORING SURVEY**

Most instruments presently available to the Armed Forces indicate only low-level beta radiation. The AN/PDR-27 series indicates  $\beta$  radiation on the external probe up to 5 mr/hr  $\beta$ - $\gamma$  (meter reading). The side window G-M survey instrument, such as the Eberline E-112B, is a low-range instrument indicating up to 20 mr/hr  $\beta$ - $\gamma$  (meter reading). The NRDL Cutie Pie, CP-3 DM, is a medium-range radiac reading up to 100 rep/hr  $\beta$ - $\gamma$ .  $\beta$ - $\gamma$  radiacs are usually calibrated against a gamma source. They require the use of a beta correction factor to relate the  $\beta$  reading to the true  $\beta$  radiation dose rate.

Fission-product contamination can produce serious skin burns from  $\beta$  radiation. The  $\beta/\gamma$  ratio for fission products may vary between 5:1 and 150:1 depending upon the age of the fission products and the point of measurement. However,  $\beta/\gamma$  ratios of 5:1 to 10:1 are most commonly observed. The  $\beta/\gamma$  ratio permits effective contamination monitoring in moderately high  $\gamma$  fields by measuring the  $\beta$ - $\gamma$  dose rate in a near-contact measurement.

$\beta$  survey procedures are similar to those for  $\gamma$  surveys with one exception. The window of the instrument must be open to include the  $\beta$  measurement. When the shield is open, the radiac measures the total radiation field ( $\beta$ - $\gamma$ ). To differentiate the  $\beta$  from the  $\gamma$ , the shield must be closed to make a  $\gamma$  only measurement. The total reading ( $\beta$ - $\gamma$ ) minus the  $\gamma$  reading gives a measure of  $\beta$  radiation.

$\beta$  and  $\gamma$  measurements are always made in a detailed monitoring survey. Some  $\beta$  measurements may be required in a gross survey, especially if personnel will be required to work in the contamination zone. The range of  $\beta$  radiation in air varies with the energy of the radiation. Because almost all  $\beta$  radiation can be shielded out with a thin piece of plastic (1/4 in.), metal (1/8 in.), or wood (1/2 in.), it is necessary to get close to the surface or the source of the radiation. The monitor must survey around any such items that might act as a shield. Since  $\beta$  radiation can produce surface effects, particular attention must be given to those areas in which personnel will be working and to contaminated equipment that will be handled.



A  $\beta\gamma$  monitoring survey includes the determination of area and near-contact dose rates, contamination of air, water, equipment, and facilities. Special attention should be given to surfaces and areas that will concentrate radioactive material and produce hot spots. Examples of such surfaces and areas are: rust spots on metal, drains, and scuppers; bends in pipes or ventilation ducts; low points in piping systems, air intake and diesel engine exhaust lines; wood; canvas; water puddles; etc.

The detailed  $\beta\gamma$  survey is performed as follows:

① When starting a monitoring survey from an area where there is no radiation, set the meter range on the most sensitive scale so that the meter will give the largest and most noticeable deflection when radiation is encountered. Conversely, in starting a survey in an area where it is known that radiation or contamination exists, set the meter on the most insensitive scale so that the radiation level may be most quickly determined.

② Keep the  $\beta$  shield open and hold it at a distance of 1 inch from the surface being monitored.



**③** Pass the probe over every object and surface that is believed to be contaminated, but avoid actually touching objects with the probe.

**④** FOR-LOW LEVEL CONTAMINATION MONITORING, PROCEED SLOWLY AND CAREFULLY. Accuracy is much more important than speed. Whenever a reading is taken, stop and hold the instrument still long enough to let the meter reach its maximum deflection (about 3 to 10 seconds, depending upon the particular instrument being used). Also, when switching from one scale to another, allow sufficient time for the instrument to come to equilibrium (3 to 10 seconds).

**⑤** If the source of radiation is not readily apparent, try to locate it by moving the instrument slowly in a systematic search for the highest radiation level. All hot spots, those areas with a radiation level ten times greater than the average, should be accurately defined.

**⑥** Upon locating the source, measure the  $\gamma$  dose rate at waist-height and at near-contact (1 inch) and measure the  $\beta$  dose rate at near-contact. Be sure that the exposed portion of the G-M tube or the open-window area of other types of instruments is directed toward the radiation source.

**⑦** Record the results, noting the distance of the instrument relative to the object or surface being monitored. Also indicate the type of monitoring instrument being used to show correlation of the data to measurements made with other types of instruments. (Example: 2.3 mr/hr beta shield open at 1 inch, AN/PDR-27F)

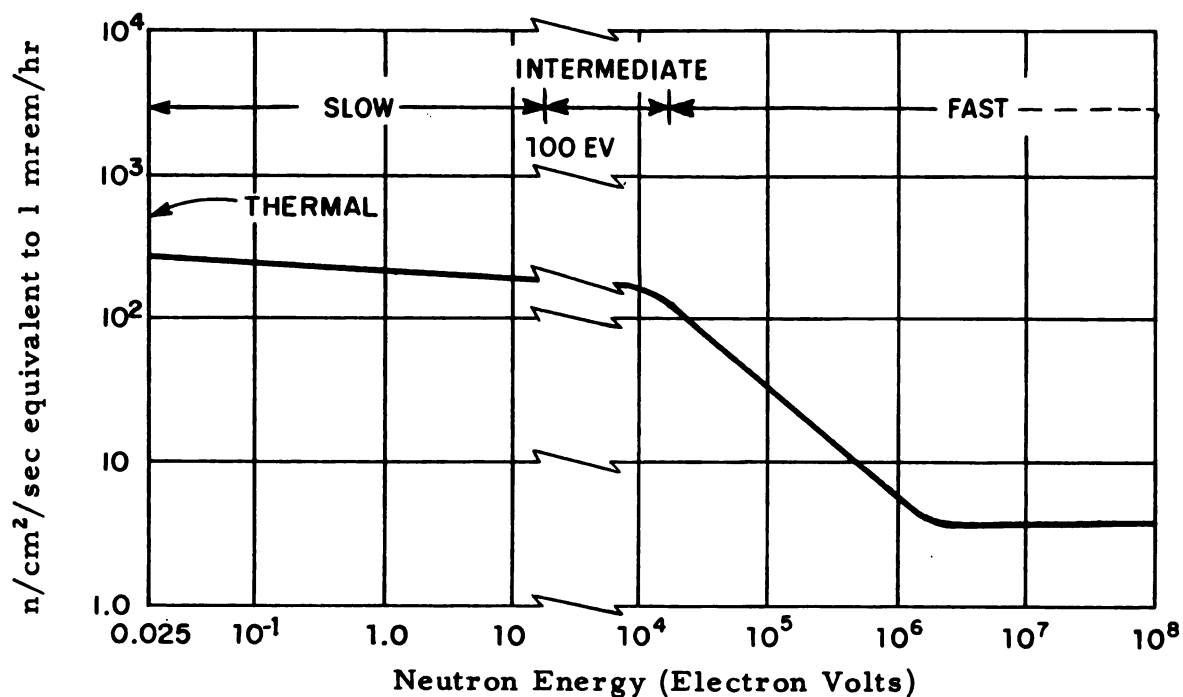
**⑧** If a field of radiation is located that causes the meter to go off scale on the highest range, obtain a higher range instrument for further measurements.

**⑨** Post radiation warning signs, indicating the presence and the magnitude of the radiation. Tag and mark contaminated equipment.

Neutron monitoring will be required in and around reactor and particle accelerator installations and areas where neutron sources such as RaBe, PoBe, etc. are stored and used. Neutrons are produced in nuclear detonations but exist for only a short period of time (less than 1 minute); therefore, no field neutron monitoring requirements exist. Volume III, Chapter 3 and Appendix B of this Volume describe some of the methods and instruments used to detect the fast and thermal neutrons.

Monitoring neutron radiation fields is a complex undertaking. In order to make an accurate evaluation of the rem dose rate, one is required to measure the complete energy distribution. There are few commercial or military radiacs that are capable of measuring the complete neutron spectrum. At best, neutron monitoring instruments will detect either slow or fast neutrons. These instruments do not detect the intermediate neutron energies.

The following graph is a plot of the neutron flux equivalent to 1 mrem/hr for various neutron energies taken from Table 4.2 in Chapter 4 of this Volume.



NEUTRON FLUX EQUIVALENT TO 1 MREM/HR

Inasmuch as most portable neutron detectors cannot differentiate between neutron energies other than thermal and fast neutrons, it is difficult to determine what MPE numbers should be used in a mixed energy field. The common practice in monitoring with portable neutron instruments is to use 1600 neutrons per square centimeter per second ( $\text{n/cm}^2/\text{sec}$ ) as the thermal-neutron flux equivalent to 6 mrem/hr for all moderated readings. (The word "moderated" is used to describe those neutrons slowed to thermal energy by a shield of paraffin or similar material over the detector.)

Neutron radiacs are not calibrated uniformly in terms of a common meter-scale reading. The various scale readings represent the neutron reaction being measured. Examples of specific types of instruments and their ranges and units of calibration are listed below.

| INSTRUMENT                                                                     | RANGE - UNITS                                                                                                                                                      | NEUTRON DETECTOR                                                             |
|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Radiation Counter Lab<br>"Portable Survey Meter<br>for Fast and Slow Neutrons" | Slow neutrons: 0 - 300,<br>0 - 3,000, 0 - 30,000<br>$\text{n/cm}^2/\text{sec}$<br>Fast neutrons: 0 - 100,<br>0 - 1,000, 0 - 10,000<br>$\text{Mev/cm}^2/\text{sec}$ | BF <sub>3</sub> counter<br><br>Polyethylene-lined<br>proportional<br>counter |
| AN/PDR-47<br>(Interim Model)                                                   | Fast neutrons only: 0 - 5,<br>0 - 50, 0 - 500 mrep/hr                                                                                                              | Tissue-equiva-<br>lent proportional<br>counter                               |
| AN/PDR-49<br>(Interim Model)                                                   | Slow neutrons:<br>0 - 25,000 $\text{n/cm}^2/\text{sec}$<br>Fast neutrons:<br>0 - 25,000 $\text{n/cm}^2/\text{sec}$                                                 | BF <sub>3</sub> counter<br><br>Paraffin-moderated<br>BF <sub>3</sub> counter |

Most neutron detectors are also sensitive to gamma radiation. Therefore, each unit must be calibrated to determine its response to a given field. During a neutron survey of an area where gamma radiation is present, the gamma radiation must be biased (electronically subtracted) from the gamma plus neutron measurement to give the neutron measurement.

## MONITORING HIGH-ENERGY GAMMA RAYS AND PARTICLES

The preceding sections of this chapter present procedures for monitoring various radiological situations involving radioisotopes and machines that produce gamma radiations of less than 2 Mev energy. When monitoring particle-accelerating machines, special instruments or modified radiacs are required. Monitoring personnel must also be familiar with the characteristics of the machine being monitored. The radiation problems vary from one machine to another.

Radiacs used for normal survey work may be unsuited for high-energy monitoring for the following reasons: due to their design and calibration, they do not respond linearly as energy rises; the instrument time-constants are too long for pulsed machines; electron equilibrium may not be reached due to the thickness of the chamber walls, etc. In the case of a pulsed radiation source of 180 pulses per second, each lasting only a few microseconds, an ionization chamber with a long time-constant compared to the time between pulses will indicate an average (integrated) intensity that may be in the order of 1/1000 of the instantaneous intensity. In the case of neutron instruments, the interpretation of neutron flux depends on the energy spectrum and on the chamber design. When the chamber dimensions are small, compared to the proton-recoil range, the instrument response is tissue-equivalent from about 0.1 Mev to perhaps 3 or 4 Mev but will drop rapidly at higher energies unless an additional hydrogenous chamber is used. Similar problems will be found with other types of particles.

Additional caution should be taken in monitoring high-energy radiation machines for those radiations that are produced in other than the target area. Often this stray radiation is of small angle and high intensity. In such a case, the response time of the instrument must be known so that such stray beams are not overlooked by monitoring the area too rapidly.

More detailed information on monitoring high-energy gamma rays and particles may be found in NBS Handbook No. 55, Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts and NBS Handbook No. 63, Protection Against Neutron Radiation Up to 30 Million Electron Volts.



## ALPHA (α) MONITORING SURVEY

Routine α monitoring is a qualitative determination. It requires tedious, meticulous survey techniques and the use of earphones with the instrument. A satisfactory α instrument is the Nuclear Chicago's "Pee Wee," Model 2111, or the Eberline PAC-3G. An α calibration source should always be used to establish relative audible signals during the monitoring survey since the audio response is more sensitive than the meter response. All α radiacs should be checked and adjusted to minimize sensitivity to β-γ radiations.

α instruments are usually calibrated in c/m or d/m per so many square centimeters of the probe area. Readings are recorded in activity per area. (Example: 2000 c/m/75 cm<sup>2</sup> when using the Pee Wee or 2000 d/m/150 cm<sup>2</sup> when using the AN/PDR-10.) The background reading of an α radiac should be negligible. If it is not, α contamination of the probe or improper β-γ sensitivity should be suspected. It will be necessary to decontaminate the probe or to adjust the sensitivity before reuse if low levels of contamination are to be detected.

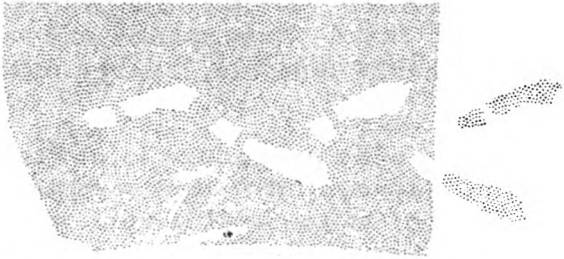
α contamination must be quickly detected and controlled because of the low MPC's of α emitters. Under normal weapon-detonation conditions, α contamination is a minor problem. However, under certain conditions, such as destruction of a nuclear weapon by fire or high explosive detonation or a low-yield nuclear explosion, etc., α emitters may become the predominant source of contamination. Detection and control of α emitters is necessary to prevent ingestion, inhalation, and the spread of α contamination. Since α particles have very short ranges (maximum range about 1 inch in air), it is essential that the detecting radiac be held AS CLOSE AS POSSIBLE (about 1/4 inch) to the surface being monitored. α radiacs utilize thin-window proportional counters or scintillation detectors which are very fragile.

**α** monitoring requires extreme care on the part of the monitor. The following procedures are recommended for **α** monitoring of large areas when sufficiently trained monitors are not available. An experienced monitor turns all instruments on, checks the calibration and indicates on each individual meter face the readings corresponding to the contamination levels of interest. The monitoring group is then assembled for general indoctrination. Special emphasis should be placed on the distance the instrument is held from the surface to be monitored (1/4 inch or less, but not touching). The group is then organized to proceed across the contaminated area in a line abreast. The experienced monitor follows the group in such a manner that he can observe all monitors. When a monitor has difficulty or locates contamination, he may signal the trained monitor to assist him or to verify his finding.

The area to be monitored may be laid off in a grid pattern and the monitors located about 100 feet apart, with the center man bearing toward the suspected center of contamination. The group proceeds toward the center, monitoring the surface at about 50 ft intervals, placing markers at the locations of detectable activity and other preselected contamination levels. Chapter 4, Fig. 4.6 of this Volume presents data to convert meter readings to surface contamination levels.

## CONTAMINATION MONITORING

Contamination monitoring consists of identifying the type and measuring the quantity of both fixed and removable radioactive materials which exist in locations where they may be harmful to personnel or where they may jeopardize industrial or laboratory operations. **RADIOACTIVE CONTAMINATION (RADIOACTIVE DIRT) IS ANY RADIOACTIVE MATERIAL THAT IS IN AN UNDESIRE**



**LOCATION. To control radioactive contamination, the monitor must determine if the contamination is FIXED or REMOVABLE. Fixed contamination may create a radiation problem, depending on the level of the contamination. Removable contamination, besides creating a possible radiation problem, is a potential source of internal body contamination.**

Contamination monitoring is performed in conjunction with beta-gamma radiation monitoring. The magnitude of the contamination will determine the monitoring method and the technique to be used.

## $\alpha, \beta, \gamma$ WIPE TEST



It is possible to detect removable contamination by wiping a clean (non-contaminated) material, such as absorbent paper (paper hand towels, toilet paper) or chemical filter paper (Whatman No. 1), over the object in question.

If the wipe procedure is carefully controlled, the wipe sample is nominally taken to represent 10% of the removable contamination. The amount of contamination picked up by a wipe depends upon the operator's technique, the type of wipe material, the chemical and physical composition of the contamination, and the surface condition of the contaminated object. Experience at USNRDL has shown that the MPC's for removable activity listed in Chapter 4 do not produce any contamination-control problems (a 10% wipe efficiency is assumed). These MPC's may still produce a technical contamination-control problem, that is, a nuisance in low background counting areas; therefore, whenever feasible, all removable contamination should be removed.

If the wipe procedure is not carefully controlled, as in gross monitoring surveys, the wipe sample provides only a relative indication of the amount of removable contamination. A positive gross wipe indicates that there is some removable contamination, while a negative gross wipe indicates that there is probably no significant removable activity. The gross wipe is essentially a "go-no-go" test for removable contamination.

The wipe sample may be counted by appropriate radiacs that will measure  $\alpha$ ,  $\beta$ , and  $\gamma$  activity. Portable instruments, such as the Eberline PAC-3G and the AN/PDR-27 series, may be used for most surveys of this type, although higher range radiacs may be required for high contamination levels. For accurate or low-level contamination determinations, counting room equipment, such as the scaler CP-79/UD with appropriate detectors, may be used.

For a general contamination survey, there is no established pressure to be applied to the wipe. In general, the type of wiping material and the surface being wiped will determine the degree of pressure used; the wipe paper should not tear. THE STANDARD WIPE PROCEDURE IS TO LIGHTLY WIPE A 12 SQUARE INCH SURFACE AREA.



ALL WIPE SAMPLE EVALUATIONS FOR  $\beta$ - $\gamma$  ACTIVITY SHOULD BE MADE WITH THE WINDOW OPEN TO GIVE MAXIMUM SENSITIVITY.

The wipe is held one inch or less from the open window of the radiation-sensitive element of the radiac instrument, and the rise above the general background is a measure of the removable activity. If the general radiation level is above 20 mr/hr, a beta-sensitive radiac, such as a Cutie Pie, must be used to monitor the wipe. Surveys for removable contamination must be made to estimate and control the spread of contamination. If the radiation background is so high that wipes cannot be evaluated immediately by portable radiacs, wipes should be taken to a low background area for evaluation or measured with laboratory counting equipment.

Wipes evaluated by counting equipment may be converted to disintegrations per minute for absolute evaluation. Counting procedures and the methods of determining disintegrations per minute are given in Appendix G. All wipe samples placed in  $\alpha$  and/or  $\beta$ - $\gamma$  detectors, such as those used with the CP-79, should be prepared in such a manner that the counting equipment is not contaminated by the wipe. GROSSLY CONTAMINATED WIPES SHOULD NOT BE PLACED IN SENSITIVE COUNTING EQUIPMENT.

To avoid misleading results, extreme care must be exercised by the monitor to insure that his supply of unused wipe sample paper does not become contaminated before use or from his hands during use. If the wipe sample is not counted immediately after sampling, the wipes should be protected until they reach the counting laboratory. Each wipe should be placed in a separate envelope or other appropriate covering. All pertinent data relating to time, date, and position of the sample should be recorded on the envelope, together with any additional information which the laboratory may find useful in making the analysis.

## AEROSOL SAMPLING AND ANALYSIS

Exposure to airborne radioactive material (radioactive aerosols) presents a serious internal contamination problem.



Radioactive aerosols range in size from below 1 micron to that which can be seen with the naked eye. The larger particles quickly drop to earth and thus constitute a radioactive dust problem. The smaller particles may float free in air or attach themselves to dust or moisture droplets in air. The bomb debris from a nuclear weapon will range in particle size from 0.1 to 5000 microns (average size of tobacco smoke is 0.3 micron, and the size of many industrial dusts is 8000 microns). The larger size particulate matter will settle out of the air fairly rapidly. Only the finely divided component of the airborne material will tend to remain suspended or will become resuspended by weather effects. Other uses of radioactive materials may also generate aerosols. The use of acid in chemical processes, sand-blasting contaminated surfaces, welding contaminated materials, driving vehicles over contaminated surfaces, etc., are known to produce aerosols.

The generation and the use of radioactive gases also present inhalation problems. Some of the fission products are radioactive gases such as xenon, krypton, and iodine; but these gases are a problem only around experimental or reactor operations. Radon and thoron are naturally occurring radioactive gases produced as decay products of the uranium and thorium in the earth. These radioactive gases attach themselves to dust particles and thus may be detected through collection and analysis of filter media. Some radioactive gases can be detected only by passing them through gas-flow ionization chambers. If the atmosphere in which radioactive gas is suspected is relatively dust free, then air-flow ionization chambers can be used for detection. Tritium gas detectors utilize air-flow ionization chambers.

Aerosol samples are taken by drawing air through a high efficiency filter paper. A vacuum-type apparatus is used to draw air through the filter. Most particulate matter which hits the paper is held back by the low porosity of the paper. It is this particulate matter which is analyzed by standard counting methods to estimate aerosol concentration. The size of the paper used depends upon the size of the holder, the flow rate of the suction unit used, and the type of counting equipment available for counting the activity on the filter. A flow meter is usually attached to the sample collector, and the air flow is adjusted to desired flow rates. A representative aerosol sample should range from 1 to 10 m<sup>3</sup> of air. (A man inhales about 10 m<sup>3</sup> of air in 8 hours of work.)

The following data should always be recorded when collecting an aerosol sample:

- ① Flow rate of collector.
- ② Total sampling time.
- ③ Location of the sampler.
- ④ Type of filter paper.
- ⑤ Type of radioactive material (if known).
- ⑥ Operations being performed during collection.

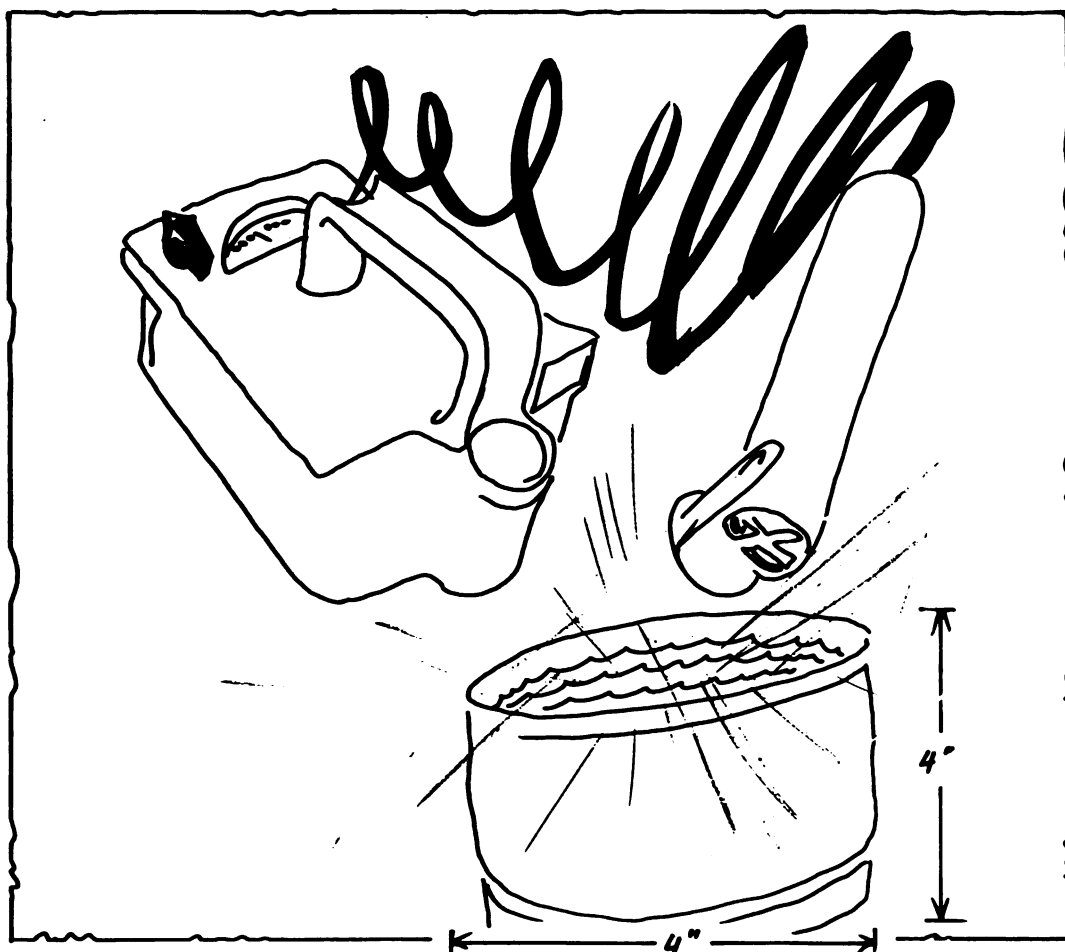
Detailed aerosol sampling and analysis procedures are given in Appendix G.

For  $\beta$ - $\gamma$  measurements of airborne concentrations of fission-products, no correction need be made for natural aerosol activity if the aerosol sample is collected in a period of less than 30 minutes. The maximum permissible air concentrations for occupational exposure are listed in Appendix A of this Volume. Chapter 4 of this Volume lists the MPC's for fission-product aerosols recommended for Special Operations.

## GROSS WATER MONITORING

Water can be monitored by measuring the radioactive material content of representative water samples taken from water supplies. Gross water monitoring, measuring the contamination level of the water with portable G-M radiacs, has a minimum range of sensitivity of around  $10^{-3} \mu\text{c/cc}$ . Gross water monitoring techniques are applicable only for early-time (less than 30 days) fission-product contamination.

Gross water monitoring can be accomplished with an AN/PDR-27 radiac by placing 1000 cc (1 qt) of the suspected water in a sample disk to provide a liquid volume of at least 4 inches in diameter by 4 inches in height. The water contamination is then proportional to the measured open window radiac reading when the probe is held 1 inch above the center of the sample disk. Always be sure to subtract the background reading.



It is important that the age of the fission products be known because their isotopic composition changes with time. The following table relates the emergency MPC's that may be consumed over a period of ten days to the age of the fission products and the AN/PDR-27 multiplying factor. The listed MPC's are based on a 25 rem dose where water consumption is assumed to be 1.5 liters per day for ten days.

**FISSION-PRODUCT CONTAMINATION LEVELS  
IN WATER AS MEASURED WITH AN AN/PDR-27 RADIAC**

| Age of Fission Product (days) | To convert net mr/hr on 27F Radiac to $\mu\text{c/cc}$ multiply by: | Acceptable limit for 25 rem exposure* $\mu\text{c/cc}$ |
|-------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|
| 1/2                           | .450                                                                | .190                                                   |
| 1                             | .130                                                                | .054                                                   |
| 2                             | .090                                                                | .024                                                   |
| 3                             | .078                                                                | .019                                                   |
| 4                             | .067                                                                | .016                                                   |
| 5                             | .060                                                                | .014                                                   |
| 6                             | .055                                                                | .013                                                   |
| 7                             | .052                                                                | .012                                                   |
| 8                             | .049                                                                | .011                                                   |
| 9                             | .047                                                                | .011                                                   |
| 10                            | .042                                                                | .010                                                   |

\* Estimated internal exposure of 25 rem if 1.5 liters per day is consumed each day for 10 days.

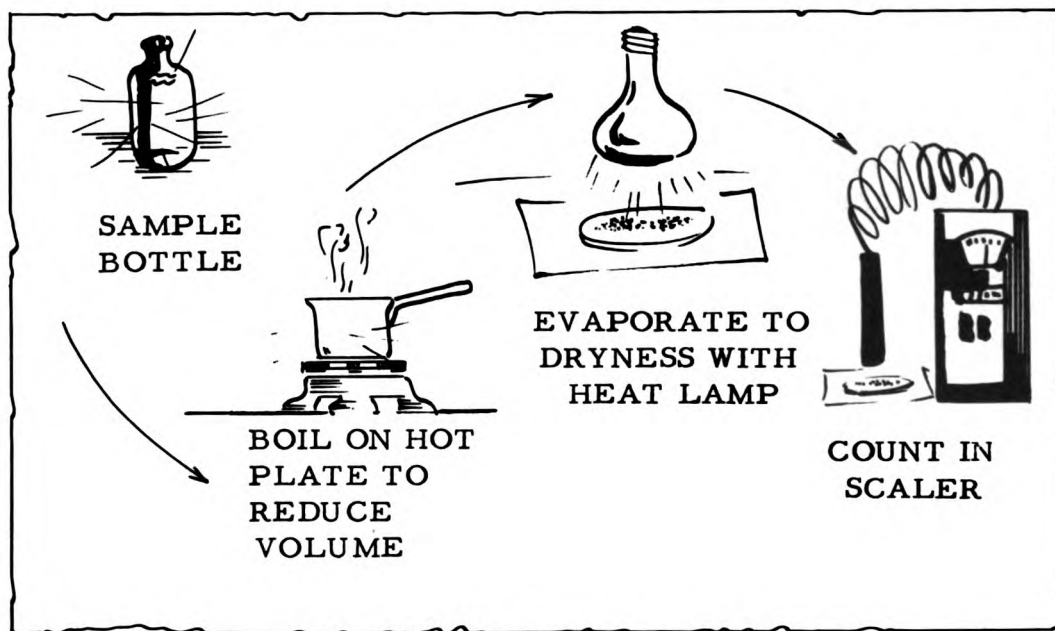
For example, assume an uncontaminated coffee can were filled with suspected water 3 days after burst and monitored with the open window of an AN/PDR-27 probe, producing a reading of 0.45 mr/hr above background; the water contamination concentration may be found by multiplying the meter reading by the multiplying factor for the third day, as follows:

$$\text{Water concentration} = 0.45 \text{ mr/hr} \times .078 \frac{\mu\text{c/cc}}{\text{mr/hr}}$$

$$\text{Water concentration} = 3.5 \times 10^{-2} \mu\text{c/cc}$$

This water concentration is approximately 2 times above the 3 day MPC value ( $\frac{.035}{.019} = 1.8 = 2$ ).

## DETAILED WATER MONITORING



Routine water monitoring is accomplished by collecting representative water samples in uncontaminated bottles. Caution should be exercised to avoid introducing contamination into the water sample from the filling spout, hands, etc. The water samples are delivered to a counting laboratory where aliquots are withdrawn and evaporated to dryness in planchets for radio-assay. (Appendix G describes counting procedures.) Water monitoring is a specialized task for the radiochemical laboratory. This method requires special radio-assay procedures for identifying and measuring the radioactive content of the water.

The MPC's for use in restricted and unrestricted areas for specific and unidentified isotopes are listed in Appendix A of this Volume. The MPC's for fission-product contamination for use in special operations are listed in Chapter 4 of this Volume. When radio-assaying water which has neutron-induced activity, such as sodium-24 in sea water, the radioactive decay rate should be determined.

Radioactive contamination may be removed from water by distillation or precipitation and efficient filtration. Chlorination or boiling will not remove the contamination.

## **FOOD MONITORING AND DECONTAMINATION**

Foodstuffs exposed to contamination or to neutron radiation during a nuclear explosion will require monitoring to determine suitability for human consumption. When exposed to fallout, the outer surfaces of either the product itself (meat, fresh vegetables) or the container will most likely be contaminated. While washing will effectively remove contamination from containers, it tends to soak radioactive contamination into the inner layers of unpackaged foods. Therefore, unpackaged meats and vegetables will best be decontaminated by removal of outer layers prior to washing.

Foodstuffs exposed to neutron radiations pose a slightly different problem since radioactivity may be induced in the packaging material or the food itself. Food or packaging materials which have a high sodium content (e. g., glass) become particularly radioactive. Certain types of metal containers can become more radioactive than others, depending on the type of coatings used on the can. The decay time for the metal cans will generally be longer than for glass. Since foods are packaged in such a manner that the contents and the containers do not react chemically, the radioactivity of the container is not transferred to the contents.

To monitor the foodstuff in either case, a beta-gamma survey of the material should be made using a contamination-type meter (G-M) with the window open, using the detailed survey procedure. A check should also be made for possible alpha contamination. All foods exposed to possible neutron irradiation should be removed from the containers and remonitored before declaring them unusable.

The general rule for consumption of contaminated foodstuff is as follows:

- A** Do not eat any contaminated or radioactive food unless in an emergency status.
- B** For emergency situations, Chapter 4 of this Volume contains a table of MPC's for food and water containing fission products.



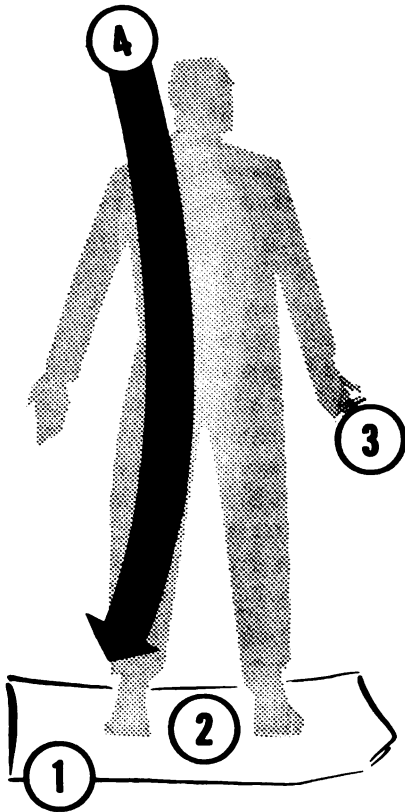
## PERSONNEL MONITORING



Personnel monitoring is performed to detect body contamination, to control exposure to spot-contamination of the skin, and to prevent the transfer of contamination into the body.

Those portions of the body and clothing that would normally become contaminated from working in a contamination area (hands, face, sleeves, seat of pants, knees, and shoes) should always be monitored. If no contamination is found on these areas, the person may be considered clean. For maximum sensitivity, the open window of a  $\beta$ -sensitive instrument should be used for personnel monitoring. Geiger-Mueller type radiacs should be used whenever the radiation background permits. The sensitive portion of the instrument should be held about 1 inch from the surface and passed slowly over all areas being monitored. Earphones are always used for personnel monitoring since the probe location and meter face cannot be watched simultaneously.

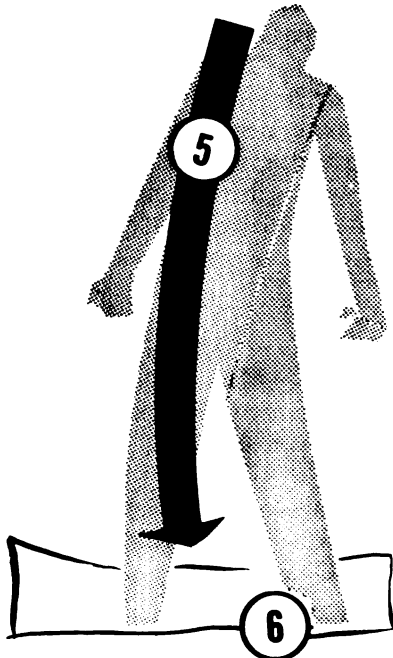
The following procedures are recommended for personnel monitoring:



① Have person stand on a step-off pad or on the contaminated side of a line or barrier.

② Instruct the person to stand straight, feet spread slightly, arms extended with palms up and fingers straight out.

③ Monitor both hands and forearms to the elbows with palms up, then repeat with hands and arms turned over.



④ Starting at the top of the head, cover the entire front of the body, monitoring carefully the forehead, nose, mouth neck line, torso, knees, and ankles.

⑤ Have the subject turn around, and repeat the survey on the back of the body.

⑥ Monitor the soles of the feet.

## **RADIOURINALYSIS**

Radio-assay of urine is the most common method used to estimate the body burden of radioactive substances. After being taken into the body, a radioactive substance will be eliminated rapidly during the first few days or weeks prior to being set or fixed in the system. The rapid initial rate of elimination may be used to roughly evaluate the seriousness of accidental ingestion, inhalation, or absorption of radioactive substances. Biological excretion data for various radioisotopes are given in Table 4.5 in Chapter 4.

A gross method for radio-assay of urine is the evaporation of a sample to dryness and subsequent counting of the residue. The sample taken can be either the complete voiding over a 24 hour period or the first voiding upon arising on two consecutive mornings. The sensitivity of the direct evaporation method (using about 150 cc of the sample) is limited by two factors: (1) the natural  $K^{40}$  activity of the urine which tends to mask traces of other radioactive substances that might be present and (2) the high concentration of solids in urine which result in self-absorption of beta particles.

The radioisotope  $K^{40}$ , occurring naturally in the potassium of urine, gives off 28.3 beta particles per gram of total potassium per second, plus 12.7 gamma rays per 100 betas. 90 d/m per gram is considered an average for beta emissions from the solids in urine. The total solids contained in the urine limit the size of the sample profitably evaporated. Sensitivity of the evaporation process may be increased by approximately a factor of 10 if the potassium is precipitated out with sodium cobaltinitrite. Other solid content can be reduced by precipitation with nitrous acid of the urea which constitutes about 40% of the total urine solids.

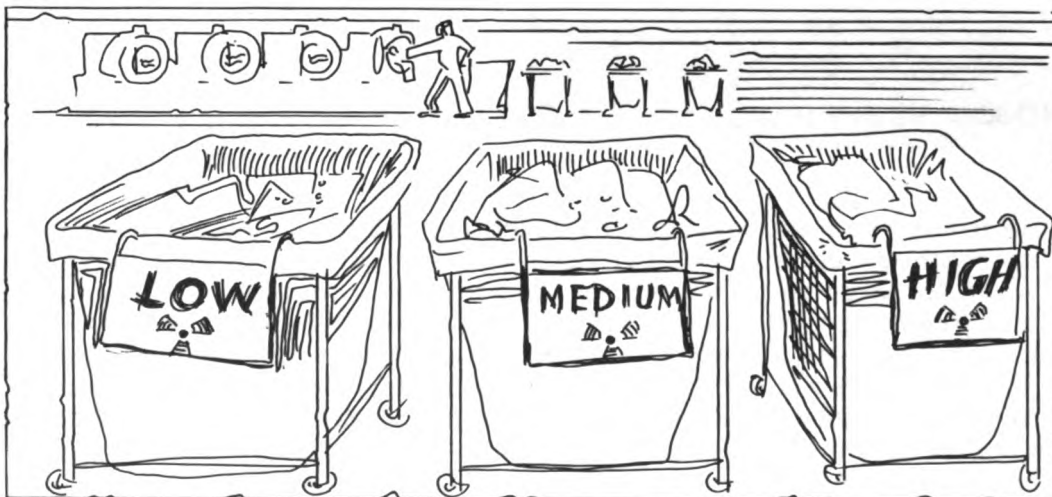
Since the direct evaporation method is not an efficient quantitative measure of beta-gamma contamination, detection of appreciable activity should be followed by a specific analysis for the suspected contaminants. Alpha contamination requires a quantitative analysis of the urine due to high absorption by the residue. Laboratory procedures for detection of isotopes are beyond the scope of this Chapter but are available in the literature.

## PROTECTIVE CLOTHING MONITORING

Monitoring of protective clothing is necessary to minimize spread of contamination and to prevent internal and body-surface contamination of personnel.

Protective clothing is monitored: (a) during use to determine when and if unsafe levels of contamination are present, (b) after use to separate clean from contaminated items, and (c) after laundering to determine if re-washing is necessary. Portable radiacs or line voltage count-rate meters may be used. Skin burns or internal body contamination may result from wearing clothing excessively contaminated with fission products or other radioactive material.

For  $\beta$  radiation, all clothing should be monitored with the open window probe held as near as possible to, but never touching, the surface.  $\alpha$  monitoring, although difficult, is necessary since contaminated protective clothing may allow transfer of the  $\alpha$  emitter into the body. As usual for all monitoring, care should be taken to prevent contamination of the monitoring instrument. Contaminated clothing should be segregated into low, medium, and high contaminated batches (< 2 mrad/hr, > 2 but < 20 mrad/hr, and > 20 mrad/hr) before laundering to prevent cross-contamination.



## **FALLOUT DETECTION**

The radiological problem produced by a nuclear weapon explosion depends upon the type of burst (surface, sub-surface, or air), the type and size of the weapon, the location with respect to ground zero, the local weather condition, and the actions undertaken in the fallout zone. In areas close to the point of detonation, the external radiation is the limiting factor. In areas distant from ground zero, fallout contamination will require dosage and contamination control at early times. A shift to contamination control is made as the age of the fission products increases. Fallout detection is necessary to effectively apply radiological countermeasures. The earlier the fallout is detected, the more effective will be the action taken to minimize external radiation exposure and internal contamination. Permanent monitoring systems equipped with appropriate alarms and readouts can be used for detection of the start and/or cessation of fallout.

### **MONITOR PREDESIGNATED AREAS**

A fallout watch is assigned on an unobstructed land or shipboard area, and specific monitoring points are designated. The radiation background in the area is noted; if high, decontaminate as practicable. A log is maintained tabulating the radiation readings each 1/4 or 1/2 hour. The monitoring geometry should be identical for all measurements at each point. A rise in the readings indicates fallout is coming down or a contaminated cloud is passing overhead with no contamination falling out. A wipe survey will indicate whether or not fallout is coming down.

### **AEROSOL SAMPLING**

One of the most efficient methods of detecting fallout is by air monitoring. This method consists of collecting an air sample in an exposed unobstructed location for a timed period and then monitoring the sample. Appendix G presents procedures for "spot" aerosol collection and analysis. Precautions should be taken to prevent contamination of the sample. Permanent air monitoring systems with alarm and continuous activity level recorders are extremely useful for fallout detectors. Such systems can detect more minute amounts of fallout than portable and/or permanent  $\gamma$  radiation monitors.

## GREASED BOARD FALLOUT COLLECTOR

Where radiation levels are such that the G-M type instrument cannot be used, a board about 1 ft x 1 ft covered lightly with grease or tape (sticky side exposed) can be placed in a designated area for a period of 15 to 30 minutes to collect the fallout. After being replaced with a second board, the exposed board is removed to a low background area to be monitored. Continuation of this procedure quantitatively measures the fallout. The area of exposure must be such that contamination from surrounding surfaces is not transferred to the board by the wind or spray. The greased board method is also useful for determining the cessation or recurrence of fallout.



## OTHER METHODS

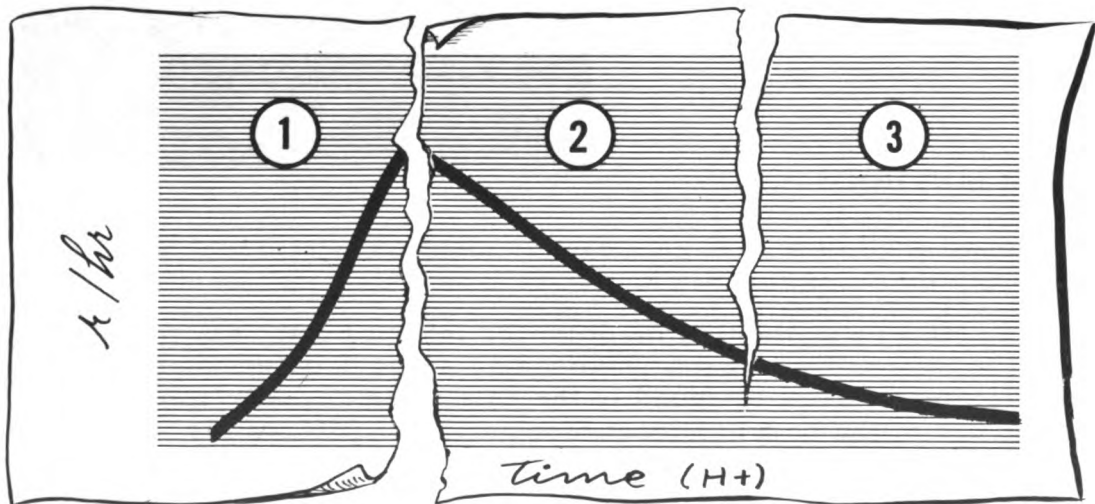
Since hair acts as a collection medium for fallout particles, monitoring personnel in exposed areas may be used as a rough detection method. Often contamination can be found in the hair when not detectable on other portions of the body. Direct monitoring of filtered air intakes on operating vehicles, in compartments, and in buildings, etc., will serve as a rough fallout detection method since each of these will concentrate particulate matter.

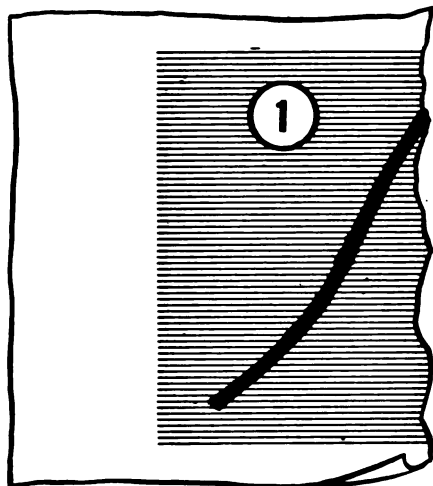
## FALLOUT CONTAMINATION

The magnitude of the external radiation and internal contamination problem produced by fallout depends upon (1) the amount and chemical characteristics of the fallout deposited in the area and (2) the age of the fallout (time from detonation). Generally speaking, the external radiation hazard should be considered first. Action should be taken to minimize external radiation exposure while concurrent action is being taken to minimize the internal body contamination. Field experience has shown that the dose from external radiation from contaminated surfaces in a fallout area exceeds the internal dose resulting from the resuspension of the contamination (see Fig. 4.3 in Chapter 4). Additionally, action taken to reduce external exposure by removing or protecting personnel automatically reduces internal contamination.

The external radiation and internal contamination problem produced by fallout may be divided into three time periods classifying the radiological countermeasures.

| TIME PERIOD           | COUNTERMEASURES                            |                       |
|-----------------------|--------------------------------------------|-----------------------|
|                       | Primary                                    | Secondary             |
| ① Radiation Buildup   | Radiation Control                          | Contamination Control |
| ② Radiation Reduction | Radiation Control<br>Contamination Control |                       |
| ③ Contamination       | Contamination Control                      | Radiation Control     |

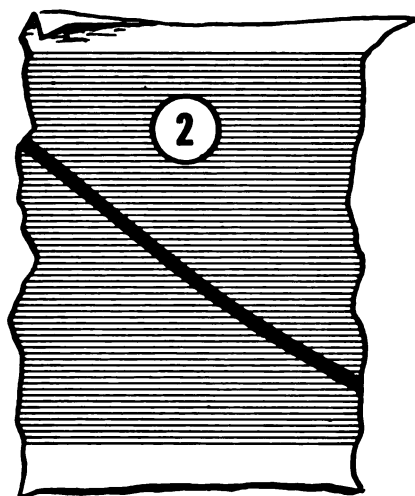




## RADIATION BUILDUP PERIOD

The radiation buildup period is the time from the start of fallout to the time when the fallout ceases or when the buildup rate is equal to or less than the decay rate. During this period the major radiological problem is to keep the external radiation dose to a minimum and to prevent internal contamination as practicable. The total time of fallout will depend on local weather conditions, distance from ground zero, type and size of the weapon detonated, chemical and physical characteristics of the fallout particles.

Primary fallout will be deposited in less than an hour in the immediate vicinity of ground zero. The heavier particles of the local fallout will be deposited within a day or two in the area downwind of ground zero; the lighter particles will take several weeks to settle to the earth in the same general latitude as ground zero. Shifting winds may bring the fallout cloud over the same area more than once.



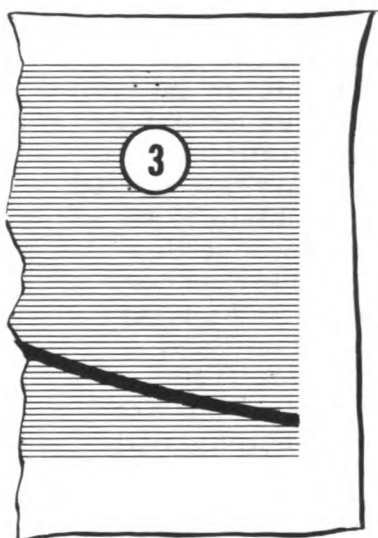
## RADIATION REDUCTION PERIOD

The radiation reduction period is the time following the cessation of fallout that is required either for natural decay or decontamination to reduce the fallout radiation intensities to levels in which the personnel can operate within established MPL's. A portion of this reduction period may be spent in the shelter area, and a portion of the time may be spent in effecting decontamination of the area. Once the radiation dose rates are reduced to levels where personnel may remain in the fallout zone for long periods of

time, the rad-safe requirements will begin to shift and more emphasis will be placed on the contamination control. This is a natural shift in effort since the external radiation problem is decreasing from the decay of the shorter-lived fission products. The longer-lived fission products become more predominant, making the control of internal contamination more critical.



## CONTAMINATION PERIOD



The contamination period occurs after the fission-product activity has decayed to a level that will produce an insignificant radiation exposure problem, even though sufficient radioactive material remains to require contamination control procedures. The contamination period will continue until the contamination has decayed or has been decontaminated to an insignificant level, a level which is no longer harmful to personnel or jeopardizing to laboratory or industrial operations.

The contamination levels listed in Chapter 4, for Final, Standard, and Operational Clearance, will determine the rad-safe working procedures necessary to control the contamination problem.

### ESTIMATING . . . TIME OF PEAK ACTIVITY OF FALLOUT TIME OF CESSATION OF FALLOUT

In nuclear weapon testing, it is important to be able to estimate the time of peak activity of fallout and time of cessation of fallout at various locations. This is important if personnel are going to occupy an area in the fallout zone. The graph on the opposite page illustrates a typical buildup and decay plot of the radiation intensity from fallout contamination at some point in the fallout zone.  $T_a$ , the time of arrival of fallout, is a measured time in hours from the time of detonation, H-hour. Methods for detecting the arrival of fallout are given on Page 176.  $T_p$ , the estimated time of arrival of peak activity in hours from H-hour, is given by

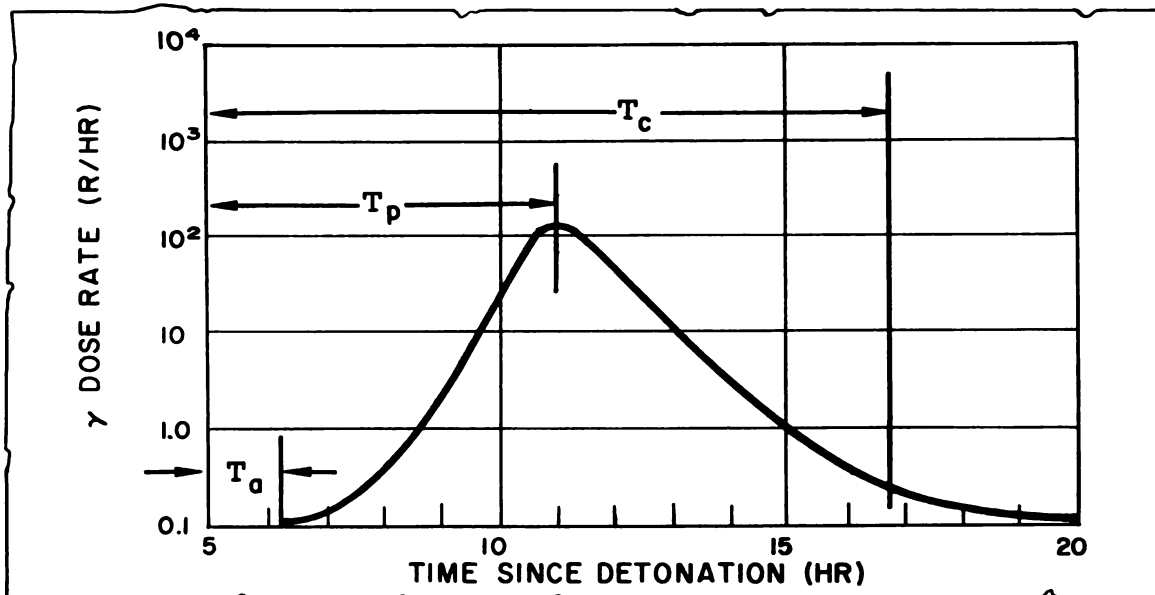
$$T_p = 2 \times T_a$$

(This approximation may vary by a factor of 2 or more)

$T_c$ , the estimated time of cessation of fallout in hours from H-hour is given by

$$T_c = 5 \times (T_a)^{0.7}$$

(The best guess to date)



$T_a$  = time of arrival in hours

$T_p$  = time of peak activity in hours

$T_c$  = time of cessation in hours ( $T_c \leq 17$  hr)

**PROBLEM:** During one of the nuclear weapons tests at the Eniwetok Proving Grounds, personnel were manning a vessel station in the fallout zone to collect fallout. The estimated time of arrival of fallout was  $H + 5$  hrs. What is the estimated time of peak activity and estimated time of cessation of fallout?

**SOLUTION:**

$$T_p = 2 \times T_a$$

$$T_c = 5 \times (T_a)^{0.7}$$

$$T_a = 5 \text{ hours}$$

**ANSWER:**

$$T_p = 2 \times 5 = 10 \text{ hours}$$

$$T_c = 5 \times 5^{0.7} = 15 \text{ hours}$$

(NOTE: 5 raised to the 0.7 power may be found by multiplying the logarithm of 5 by 0.7 and looking up the antilogarithm.)

# MONITORING RECORDS

Documentation of radiation and contamination measurements is one of the most important parts of the monitor's assignment because this information is used for the evaluation of radiological situations and for semi-legal records. All radiation measurements of significance should be recorded on monitoring forms. The monitor must always record:

- ① The object or area monitored.
- ② The location of the object or area.
- ③ The types and levels of radiation.
- ④ The amount of fixed and/or removable activity.
- ⑤ The amount of liquid and aerosol contamination.
- ⑥ The distance of the radiac from the object monitored.
- ⑦ The type of radiac used.
- ⑧ The time and the date the measurement was made.
- ⑨ His (the monitor's) name.

The names of personnel involved in radiological accidents and the conditions existing at the time should be noted. The radiation or contamination levels of items released to other activities or to unrestricted areas should be recorded. Where air, wipe, and liquid samples are taken for laboratory analysis, supplemental information is especially important for accurate assay.

Monitoring forms for recording readings should be used whenever available. These will vary in detail, depending upon the type of survey and the particular information needed for plotting charts, determining the radiological situation, and compiling reports. A typical monitoring form is shown on the opposite page. Monitoring reports are official documents, and every effort should be made to make them as accurate and complete as possible.

Very often it is not practical for a monitor to complete the monitoring form while conducting the radiological survey. The monitor may keep a working draft of the monitoring data in a pocket notebook, on 3 x 5 in. cards taped to the side of the radiac, on his sleeve or pants, or on scratch paper kept in his pockets. These data are, of course, later transcribed to the monitoring forms for the record.

Date: 1 Nov 1954Report No.: 17Location: U.S.S. MonitorDescription: Detailed Survey of #1 Whale Boat

| Time | Object Monitored                      | Instrument Used | Radiation* Level           |                |
|------|---------------------------------------|-----------------|----------------------------|----------------|
|      |                                       |                 | Meter reading and Distance |                |
|      |                                       |                 | Shield Open                | Shield Closed  |
| 1000 | Deck from stem to King post           | 27 C            | 3 mμ/h - 1"                | 2 mμ/h - 1"    |
| 1001 | Deck from King Post to housing engine | 27 C            | —                          | 10 mμ/h - 1"   |
| 1003 | Engine housing area                   | 27 C            | —                          | 6 mμ/h - 1"    |
|      | Engine Control (wipe #1)              | Berkley 2750    | 10 K c/m                   | 5 K c/m        |
|      | Fire extinguisher (wipe #2)           | "               | 18 K c/m                   | 11 K c/m       |
| 1015 | Tiller (line wrapped area)            | 27 C            | —                          | 15 mμ/h - 1"   |
|      | Tiller (wipe #3) (line wrapped)       | Berkley 2750    | 40 K c/m                   | 22 K c/m       |
|      | "                                     | cutie Pie       | @ 1" 500 mμp/h             | @ 1" 100 mμp/h |

ments: Deck King post to engine covered w/ waterEngine compartment has film of greaseTiller line wrapped (highest outer - awd)

A. Vatcher BA12  
(Monitor)

## THE KEY SORT CARD

The use of key sort cards is an efficient system for recording large volumes of monitoring data. The key sort card below is a typical example showing how the card may be indexed to provide a variety of data combinations. The card may be keyed by date, project, monitoring survey type, location, etc. The reverse side of the card may be used for recording the detailed monitoring data.

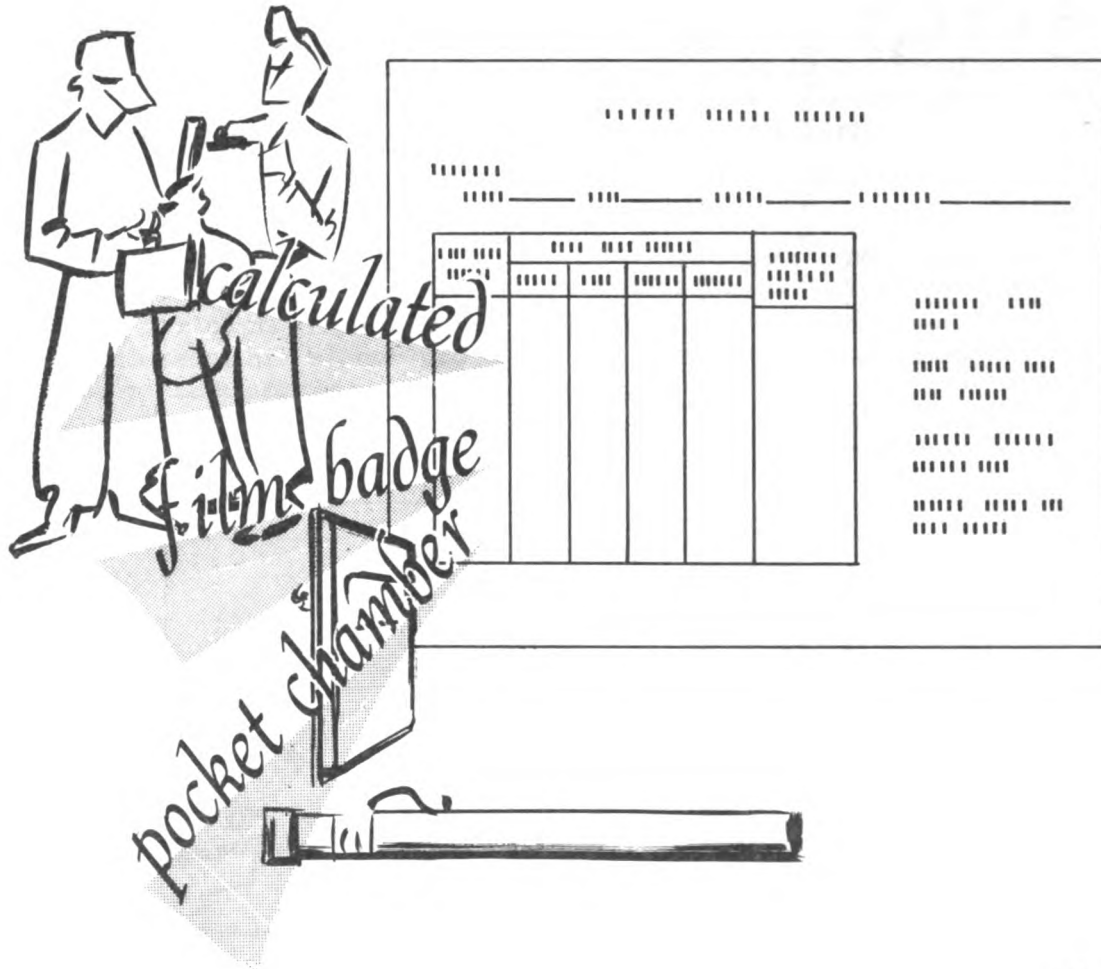
The key sort card is a complex form designed for data entry and indexing. It features multiple sections and fields for recording monitoring data. The card is divided into several main areas:

- Top Section:** Contains fields for location (e.g., TARE, WILLIAM, OTHER ATOLLS, LAGOON, OFF SHORE, ELMER, FRED, IRENE, JANET, URSULA, OTHER ATOLLS), date (MONTH, TENS, UNITS), and project (PROJECT, FILM, OTHER, YAG-39, YAG-40, LST-411, AERIAL, BARGE, RAFT, SKIFF, SMALL BOAT, OTHER, DOSAGE, CLOTHING, SKIN, MINOR INJURY, OTHER, AIR SAMPLES, LIQUID SAMPLES, WIFE SAMPLES, RADIATION SURVEY, CONTAMINATION, SHIP DECON, EQUIP DECON, FINAL CLEARANCE, OPER CLEAR).
- Middle Section:** Contains fields for monitoring (MONITOR, INSTRUMENT USED), date (DATE, TIME START, TIME STOP), and project (PROJECT, FILM, OTHER, YAG-39, YAG-40, LST-411, AERIAL, BARGE, RAFT, SKIFF, SMALL BOAT, OTHER, DOSAGE, CLOTHING, SKIN, MINOR INJURY, OTHER, AIR SAMPLES, LIQUID SAMPLES, WIFE SAMPLES, RADIATION SURVEY, CONTAMINATION, SHIP DECON, EQUIP DECON, FINAL CLEARANCE, OPER CLEAR).
- Bottom Section:** Contains fields for location (e.g., TARE, WILLIAM, OTHER ATOLLS, LAGOON, OFF SHORE, ELMER, FRED, IRENE, JANET, URSULA, OTHER ATOLLS, LAGOON, OFF SHORE), date (MONTH, TENS, UNITS), and project (PROJECT, FILM, OTHER, YAG-39, YAG-40, LST-411, AERIAL, BARGE, RAFT, SKIFF, SMALL BOAT, OTHER, DOSAGE, CLOTHING, SKIN, MINOR INJURY, OTHER, AIR SAMPLES, LIQUID SAMPLES, WIFE SAMPLES, RADIATION SURVEY, CONTAMINATION, SHIP DECON, EQUIP DECON, FINAL CLEARANCE, OPER CLEAR).

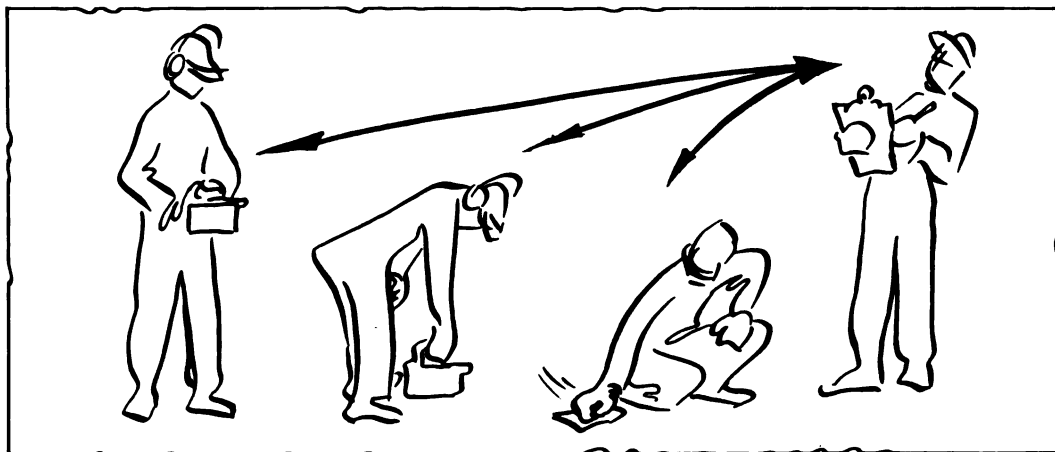
The card is designed to be indexed for different data combinations, allowing for efficient recording and retrieval of monitoring data.

## PERSONNEL EXPOSURE RECORDS

For the best utilization of manpower, and for medical and legal purposes, the radiation exposure of each individual should be recorded. Since the permissible exposure to types of radiations (penetrating and non-penetrating) and parts of the body (whole body or extremities) vary, it is recommended that three records be maintained for each individual. These records would indicate the whole-body exposure to penetrating radiation, exposure to the skin of the whole body resulting from penetrating and non-penetrating radiation, and the exposure to the extremities. The card on Page 186 illustrates a form that may be used to keep the recommended records. Additional information on the form indicates the method of monitoring, and the status of the individual's Lifetime Accumulated Dose or MPD.

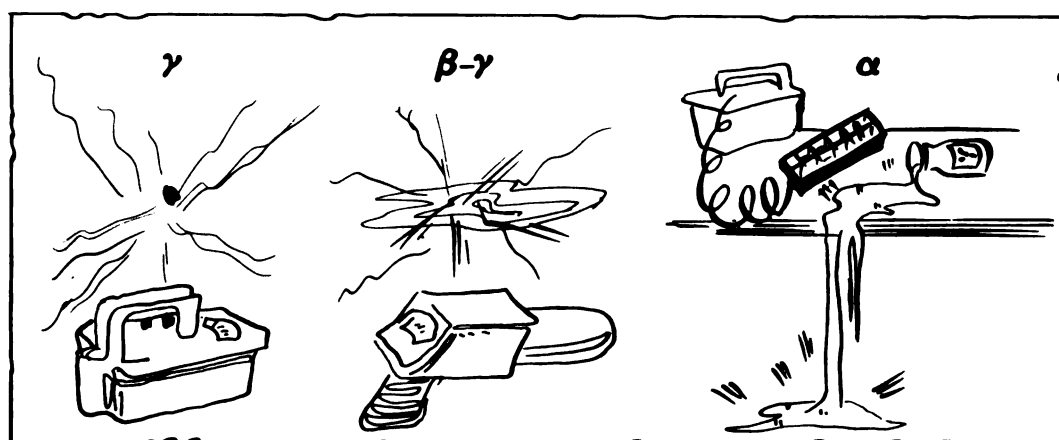




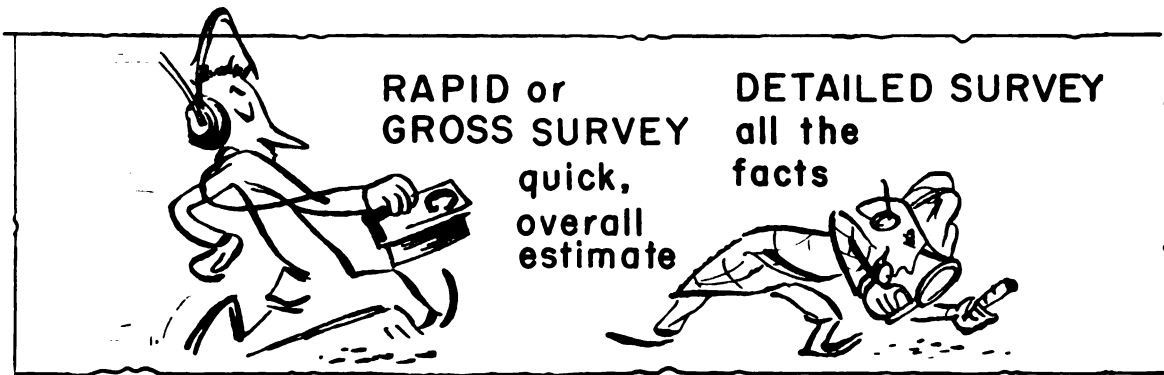


The assessment of any radiological situation requires uniform monitoring procedures and accurate data recording. Although the rules for correct monitoring seem complicated at times, constant observance of these rules will result in their becoming automatic to the monitor. Unless the monitor knows the capabilities and limitations of each monitoring instrument, much of his work could be wasted effort.

Particular problems exist concerning alpha and beta emitters and gamma rays. Chapter 3 noted specific instruments which apply when monitoring for each of the above. The monitor must fully understand the proper use of his electronic tools. Monitoring teams must always carry complete equipment.

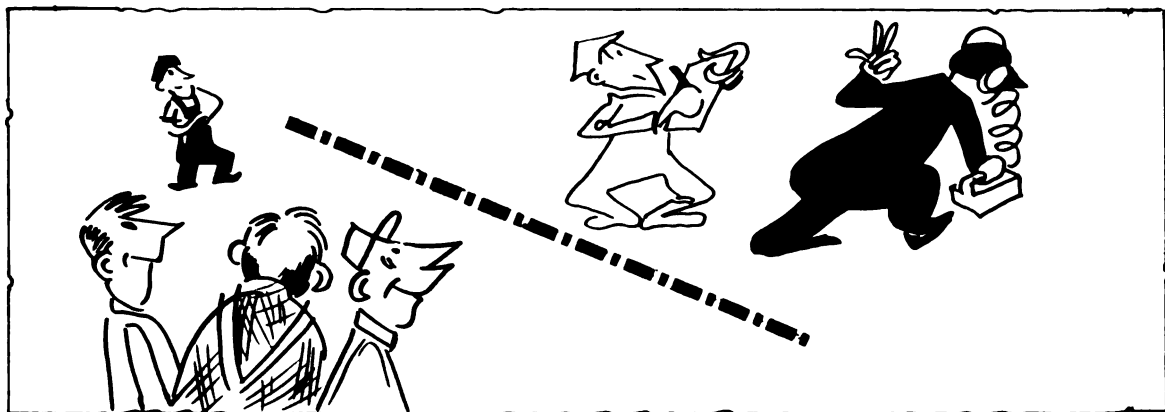






The rapid or gross monitoring survey and the detailed survey, both mentioned in previous chapters of this manual, were discussed fully. Specific situations were explained where each of the methods would be employed. The monitor will probably be called upon to use the constant-reading method and the in-and-out method, both of which were explained.

Extreme care must be exercised when monitoring because of the possibility of danger to personnel. If the job is not done correctly and thoroughly, harmful effects could be experienced not only by the radiation monitor but also by personnel who would later occupy the area which they believed to be safe. Chapter 3 listed several accurate and easily performed instrument checks with which the monitor must be familiar. Because the field of radiological safety is a comparatively new but rapidly expanding part of our lives, those people engaged in rad-safe work must rely on information gained from past experiences. Therefore, one thing of prime importance is that the monitoring teams keep regular, accurate, and uniform records of their experiences in the field.



## **CHAPTER**

# **4**

## **MAXIMUM PERMISSIBLE LIMITS (MPL) FOR CONTROLLED AND SPECIAL OPERATIONS**

An attempt is made to control the biological damage to man by establishing limits on the amount of radiation a person is permitted to receive and by establishing limits for the concentrations of radioactive materials in the body. Radiation exposure limits recommended in this Chapter represent what is believed to be the best available data on the subject, but these limits are subject to revision as experience broadens in this field. Everybody working with ionizing radiations must have adequate experience or training in order to minimize or eliminate the radiological hazard to himself and his co-workers. The responsibility for safety rests primarily with the individual.

EXPOSURE TO IONIZING RADIATIONS SHOULD ALWAYS BE KEPT TO A MINIMUM since, strictly speaking, there is no such thing as a tolerance dose when all of the possible effects of radiation on the individual and future generations are included. However, it is often impractical, if not impossible, to eliminate exposure completely. Therefore, it is necessary to establish a maximum permissible accumulated dose (MPD) that an individual may receive, compatible with his age, to prevent appreciable bodily injury to himself or the population (from the genetic viewpoint).

To keep within the MPD, we establish: a) a maximum permissible exposure (MPE) to various ionizing radiations received in operationally significant time periods, b) a maximum permissible body burden (MPBB) for each radioisotope in the human body, c) a maximum permissible concentration (MPC) for each radioisotope that might be in air or water, and d) a maximum permissible limit (MPL) for contaminated surfaces.

The MPD and MPL are based on that dose of ionizing radiation that, in the light of present day knowledge, is not expected to cause appreciable bodily injury. As used here, "appreciable bodily injury" means any bodily injury or effect that the average person would regard as being objectionable and/or which competent medical authorities would regard as being harmful to the health and well-being of the individual. The maximum permissible amounts of radioactive isotopes in the human body (body burden) represent that amount of radioactive material in the body which will not produce a dose greater than the MPE. The MPC's represent that concentration of radioactive isotopes in air and water which, when taken into and eliminated from the body at normal physiological rates, will not produce a dose greater than the MPE.

The values adopted for these permissible limits are necessarily arbitrary. Where radioactive materials have been obtained from the AEC, the ruling values have been published in the Federal Register, Title 10, Part 20 (10 CFR 20) Standards for Protection Against Radiation. These and current instructions of the Bureau of Medicine and Surgery, as well as the statutes in such States as have as yet adopted any, are in general agreement with the values promulgated by the International and National Committees on Radiation Protection as published in the several handbooks of the National Bureau of Standards (NBS).

We distinguish two situations: (1) CONTROLLED OPERATIONS, ruled by the permissible exposure rates to employees in the ordinary work week, and the possibility of exposure to other persons outside the controlled area, (2) SPECIAL OPERATIONS, in which the doses are held within the limits by regulating who may perform the operation and for how long. (Exposure of a person for his own good as in medical diagnosis or therapy does not come within the competence of these regulations. Large, accidental over-exposures are by definition "not permissible.")

In addition to establishing radiological controls on personnel working in radiation areas, it is necessary to control the movement of radiating materials. Fig. 4.1 shows the terms which are used to define radiological situations categorized in this manual.<sup>1</sup>

## **CONTROLLED OPERATIONS AND GENERAL RELEASE**

### **EXTERNAL EXPOSURE**

**UNLIMITED ACCESS WITHIN A RESTRICTED AREA** Film badges and other dosage control precautions are not necessary where the radiation levels are such that it is impossible to get more than half of the 5 rem per year MPD, or where a period of personnel monitoring has shown that nobody does get more than 50 mrem per week.<sup>1</sup>

**LIMITED ACCESS WITHIN A RESTRICTED AREA** For SPECIAL OPERATIONS there is no limit on the distribution of dose in time as long as the total comes within the permissible 12 rem in any year and the permissible accumulation (N-18)•5 rem. For ordinary CONTROLLED OPERATIONS, however, the exposure in any quarter (3 months) must be held to less than 3 rem (may be received in a single or multiple exposure). Table 4.1 lists the maximum permissible dose in significant body organs under various conditions of exposure.<sup>1, 2, 3</sup>

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Note: References for Chapter 4 are listed on Page 215.

Fig. 4.1

## DELINEATION OF RADIATION AND CONTAMINATION ZONES

### DOSAGE CONTROL

**UNRESTRICTED AREA** - any area where entry is not controlled; unlimited access to the general public.

**RESTRICTED AREA** - an area where entry is controlled and where the occupational exposure of personnel to radiation or radioactive material is controlled by a radiological safety officer. No film badges or dosage control procedures are required if the total radiation dose to personnel is less than 50 mrem/wk.

NO  
FILM  
BADGES  
50 mrem/wk

### CONTAMINATION CONTROL

**FINAL CLEARANCE** - suitable for general release to the public; no radiological hazard.

**STANDARD CLEARANCE** - nominal radiological hazard not too great for ordinary operational use in a restricted area.

**DANGER  
RADIATION**

**RADIATION AREA** - any restricted area where the radiation or contamination level is such that a major portion of the body could receive greater than 5 mrem/hr or may produce, in five consecutive days, a dose greater than 100 mrem; dosage and contamination control procedures required.

**HIGH RADIATION AREA** - any restricted area where the radiation or contamination level is such that a major portion of the body could receive greater than 100 mrem/hr; dosage and contamination control procedures required.

WEAR  
FILM  
BADGES

**DANGER  
CONTAMINATION**

**OPERATIONAL CLEARANCE** - radiological hazard requiring limited access in a restricted area; radiation and contamination control procedures required.

TABLE 4.1\*  
MAXIMUM PERMISSIBLE DOSES

| Type of Radiation                                                            | Part of Body                                                                  | Quarterly Limit | Yearly Limit For Those Whose Past Exposures Total Less than (N-18)•5 rem | Yearly Limit For Those Previously Exposed to Radiation of Unrecorded Amount | Maximum Permissible Accumulated Dose Not to Exceed |
|------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------|--------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------|
| Neutron, gamma and X ray (half-value layer >1 mm soft tissue) (DEEP DOSE)    | Whole Body, Gonads, Active Blood-forming Organs, Head and Trunk, Lens of Eyes | 3 rem           | 12 rem                                                                   | 5 rem                                                                       | (N-18)•5 rem<br>(N is person's age)                |
| Gamma and X ray and beta (half-value layer <1 mm soft tissue) (SURFACE DOSE) | Skin at basal layer of epidermis in parts of body not limited as below        | 6 rem           | 24 rem                                                                   | 10 rem                                                                      | (N-18)•10 rem                                      |
| Any                                                                          | Skin at basal layer of epidermis of hands and forearms, or feet and ankles    | 25 rem          | 100 rem                                                                  | 75 rem                                                                      | (N-18)•75 rem                                      |

\* These are guides. Specific requirements for AEC licensees (which may differ in some cases) are listed in 10CFR20.

The relationship<sup>4</sup> of neutron dose rate to neutron flux of various energies is given in Table 4.2.

TABLE 4.2

NEUTRON ENERGIES AND DOSE EQUIVALENTS

| Neutron Energy (Mev) | RBE  | n/cm <sup>2</sup> /sec to give dose of 1 mrem/hr | n/cm <sup>2</sup> /sec to give dose of 100 mrem/40 hr | n/cm <sup>2</sup> /sec to give dose of 300 mrem/40 hr |
|----------------------|------|--------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------|
| Thermal              | 3    | 268                                              | 670                                                   | 2000                                                  |
| 0.001                | 2    | 200                                              | 500                                                   | 1500                                                  |
| .005                 | 2.5  | 228                                              | 570                                                   | 1700                                                  |
| .02                  | 5    | 112                                              | 280                                                   | 850                                                   |
| .1                   | 8    | 32                                               | 80                                                    | 250                                                   |
| .5                   | 10   | 12                                               | 30                                                    | 90                                                    |
| 1.0                  | 10.5 | 7.2                                              | 18                                                    | 55                                                    |
| 2.5                  | 8    | 8                                                | 20                                                    | 60                                                    |
| 5.0                  | 7    | 7.2                                              | 18                                                    | 55                                                    |
| 7.5                  | 7    | 6.8                                              | 17                                                    | 50                                                    |
| 10                   | 6.5  | 6.8                                              | 17                                                    | 50                                                    |
| 10 to 30             | ---  | 4                                                | 10 <sup>a</sup>                                       | 30 <sup>a</sup>                                       |

<sup>a</sup> Suggested limits

**CALCULATION OF EXTERNAL EXPOSURE** When a person is subjected to a mixture of ionizing radiations, the contribution of each type of radiation must be evaluated to determine the total dose for each critical region. To demonstrate this point, the dose of penetrating radiation received by a person working for two hours in a mixed radiation field would be calculated as follows:

|                             |                            |
|-----------------------------|----------------------------|
| Gamma dose rate             | 50 mr/hr                   |
| Thermal-neutron flux        | 700 n/cm <sup>2</sup> /sec |
| Fast-neutron flux (2.5 Mev) | 380 n/cm <sup>2</sup> /sec |

Step 1: Gamma dose: 50 mr/hr x 2 hr = 100 mr = 100 mrem  
(1 mr of gamma is equal to 1 mrem)

Step 2: Thermal-neutron dose:  $\frac{700 \text{ n/cm}^2/\text{sec}}{268} \times 2 \text{ hr} = \underline{5 \text{ mrem}}$

(From Table 4.2, 268 n/cm<sup>2</sup>/sec = 1 mrem/hr)

Step 3: Fast-neutron dose:  $\frac{380 \text{ n/cm}^2/\text{sec}}{8} \times 2 \text{ hrs} = \underline{95 \text{ mrem}}$

(From Table 4.2,  $8 \text{ n/cm}^2/\text{sec}$  (2.5 Mev) = 1 mrem/hr)

Step 4: Total dose: 200 mrem

(In these calculations, the decrease of depth dose by absorption in overlying tissue and the increase by scattering within the body are ignored, although they may not exactly balance.)

Consider the same radiological situation as the above with the addition of beta radiation. Assume the beta dose rate being received by the person was 600 mrad/hr.

Step 1: Beta dose:  $600 \text{ mrad/hr} \times 2 \text{ hr} = 1200 \text{ mrad} = \underline{1200 \text{ mrem}}$   
(1 mrad of beta radiation is equal to 1 mrem)

NOTE: Since the beta radiation has a low penetrating power, producing only surface effects, it does not add to the whole-body exposure (deep dose) received from penetrating radiation. Therefore, the deep dose is still only 200 mrem. (Beta not penetrating enough to reach the lens of the eye.)

Step 2: The 200 mrem from the gamma and neutron radiations have contributed to the skin dose: 200 mrem

Step 3: Total skin dose: 1400 mrem

**CALCULATION OF MPD** From Table 4.1, the MPD for deep dose from neutron and gamma radiation is  $(N-18) \cdot 5 \text{ rem}$ . A person 30 years old would have an MPD of  $(30-18) \cdot 5 \text{ rem} = 60 \text{ rem}$  in his "dosage bank." If it is known that the person had no previous exposure, he could draw upon this reserve at a maximum rate of 12 rem per year. When he has used up his dosage savings, he could then draw only at the accumulation rate of 5 rem/yr. He may exceed 5 rem/yr only when exposure records show that his accumulation is again below the age-permissible dose,  $(N-18) \cdot 5 \text{ rem}$ .<sup>2</sup>

## MPBB'S FOR INTERNAL BODY CONTAMINATION

Internal body contamination results from the accumulation in the tissues of radioactive materials that have entered the body by absorption, inhalation or ingestion. Once within the body, they irradiate it continuously

until eliminated or decayed away. Different elements accumulate preferentially in different organs. The organ in which radioactivity first reaches the permissible limit is called the critical organ for that isotope.<sup>2</sup>

The total amount in the body is called the body burden. The maximum permissible body burdens (MPBB) have been decided from the observed body distributions, rates of elimination and organ vulnerabilities.

Even small amounts of isotopes whose biological and physical half-lives are both long, irradiate the body to a large total dose. Table 4.3 shows selected radioisotopes graded according to relative internal contamination hazard.<sup>5</sup> When handling the more dangerous isotopes, even small quantities require very tight control. Maximum permissible body burdens (MPBB) for specific radioisotopes are listed in Table III of Appendix A of this Volume.<sup>2</sup>

## **MPC'S FOR AIR AND WATER**

To be airborne, the material must be finely divided. Particles small enough to reach the air sacs in the lungs are well absorbed even though in chemical form ordinarily considered insoluble. Larger particles are coughed up and swallowed. For these and material entering in food and water, the solubility is a critical factor in their absorption. Unabsorbed material may irradiate the mucous surfaces for a time, but long continued internal irradiation comes only from the portion that is absorbed. The internal hazard from contamination of air and water, therefore, depends not only on the isotope, its concentration and the duration of exposure, but also on its chemical form and particle size.

If the contamination is identifiable, the maximum permissible concentrations in air and water for occupational exposures of 40 and 168 (continuous) hours per week may be obtained from Tables I and II, respectively, Appendix A, of this Volume.<sup>2</sup> Maximum permissible concentrations of unidentifiable mixtures also are listed in Appendix A. The maximum permissible concentrations allowed in air and water for continuous non-occupational exposure (outside of the controlled area) are 1/10 of the values for a 168 hour week listed in Table II of Appendix A.

The airborne concentrations for which the several protective equipments are adequate are listed in Table 4.4, presuming occupational exposure (40 hrs/wk) to alpha or beta contamination not further identified.



TABLE 4.3

## HAZARD FROM ABSORPTION INTO THE BODY

| Group                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Activity Scale |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| 1. SLIGHT HAZARD<br>*Na <sup>24</sup> , K <sup>42</sup> , Cu <sup>64</sup> , Mn <sup>52</sup><br><br>*As <sup>76</sup> , As <sup>77</sup> , Kr <sup>85</sup> , *Hg <sup>197</sup>                                                                                                                                                                                                                                                                                                                                                                                |                |
| 2. MODERATELY DANGEROUS<br>H <sup>3</sup> , C <sup>14</sup> , P <sup>32</sup> , Na <sup>22</sup> , S <sup>35</sup><br>Cl <sup>136</sup> , Mn <sup>54</sup> , *Fe <sup>59</sup> , *Co <sup>60</sup><br>Sr <sup>89</sup> , *Cb <sup>95</sup> , *Ru <sup>103</sup> , Ru <sup>106</sup><br>Te <sup>127</sup> , Te <sup>129</sup> , I <sup>131</sup> , *Cs <sup>137</sup><br>*Ba <sup>140</sup> , *La <sup>140</sup> , Ce <sup>141</sup><br>Pr <sup>143</sup> , *Nd <sup>147</sup> , *Au <sup>198</sup><br>*Au <sup>199</sup> , Hg <sup>203</sup> , Hg <sup>205</sup> |                |
| 3. VERY DANGEROUS<br>Ca <sup>45</sup> , Fe <sup>55</sup> , Sr <sup>90</sup> , Y <sup>91</sup><br>*Zr <sup>95</sup> , Ce <sup>144</sup> , Pm <sup>147</sup><br>Bi <sup>210</sup> , Pu <sup>239</sup> , *Ra <sup>226</sup> (in equilibrium)<br>*Principal gamma emitters                                                                                                                                                                                                                                                                                           |                |

Activity to be handled in Laboratory

- NOTES: 1. Effective radiotoxicity is obtained from consideration of the following factors: half-life, energy and character of radiations, selective localization in the body, rates of elimination, quantities involved, and modes of handling in typical experiments.
2. The slant boundaries between levels indicate borderline zones and emphasize that there is no sharp transition between the levels and the protection techniques required.
3. The above hazard groupings cannot be taken as applying to external irradiation.

TABLE 4.4

## RESPIRATORY PROTECTIVE EQUIPMENT FOR UNIDENTIFIED PARTICULATE AIRBORNE CONTAMINATION

| Radioactive Material  | Concentration                                                                                                                           | Protective Equipment Required                                                                                                                             |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alpha<br>Beta-gamma * | $< 10^{-12} \mu\text{c/cc}$<br>$< 3 \times 10^{-10} \mu\text{c/cc}$                                                                     | None                                                                                                                                                      |
| Alpha<br>Beta-gamma   | $\geq 10^{-12} \mu\text{c/cc}$ but $< 10^{-8} \mu\text{c/cc}$<br>$\geq 3 \times 10^{-10} \mu\text{c/cc}$ but $< 10^{-6} \mu\text{c/cc}$ | If oxygen in the air is adequate and no toxic gases present, use:<br>① Army Assault Mask M9A1, or<br>② Navy Combat Mask MK- V                             |
| Alpha<br>Beta-gamma   | $> 10^{-8} \mu\text{c/cc}$<br>$> 10^{-6} \mu\text{c/cc}$                                                                                | ① Rescue Breathing Apparatus<br>② Positive Pressure Mask with uncontaminated air or oxygen supply, or,<br>③ Mask with self-contained air or oxygen supply |

\* If  $\text{Pb}^{210}$ ,  $\text{Ac}^{227}$ ,  $\text{Ra}^{228}$ , and  $\text{Pu}^{241}$  are not present or the concentrations are less than 10% of the values given in Appendix A.

At levels of air contamination 10 times above the occupational MPC's listed in Appendix A (Table 1) an Army M9A1 assault mask or a Navy MK-V combat mask should be worn if exposure is to be more than one hour. At levels of 10,000 above the occupational MPC's, a mask with a self-contained air supply should be worn no matter how short the exposure time. It should be mentioned that some radioactive aerosols, such as tritium water vapor, can be absorbed through skin. In these cases, an impermeable suit must be used in addition to a mask.

## BIOLOGICAL EXCRETION DATA

Most radioisotopes, if present in the body, are excreted in measurable amounts in the urine and feces. In some cases, their radioactive decay products are excreted (radon and thoron from radium deposited in the lungs are excreted in the breath). MPC's are set for the urine, not on the basis of harm to the bladder, but because of the body burden to be inferred. To date; urinalysis is the most widely used diagnostic method for the determination of internal contamination, although for many isotopes, especially those which enter the body by ingestion, the greater portion of the isotope is eliminated via the feces.

Table 4.5 lists the permissible body burden and the fraction that appears in the excreta for some radioisotopes.<sup>6,7</sup> The elimination rates are estimated at six (6) months after absorption. This lends a factor of safety inasmuch as most personnel will be checked before this period when the excretion rate is higher. The data in Table 4.5, taken from Reference 6, were corrected to conform to the current body burden values given in Reference 2. In addition to the data given in Table 4.5, the reader is referred to the work of Langham.<sup>8</sup>

Whenever the urine activity is significant, a sequence of urine samples must be obtained in order to determine the rate of change of excretion. Each urine sample should usually be a complete 24 hour voiding. Much more than routine care and cleanliness is required to avoid vitiating the analysis by the inadvertent introduction of a little contamination from hands, dust, dirty containers, etc. (For those isotopes that leave the body slowly, it is advisable to make collections directly into new bottles.) Estimation of body burden from the urinary assays requires application of formulae which include: the chemical and physical characteristics of the material (particle size, solubility, etc.); the method by which it entered the body (operational conditions); the time the exposure began and how long it lasted (for fission products the date of fission should be known); the time the urine sample was collected in reference to the time of exposure; and the person's previous exposure record.

## MPL'S FOR SKIN CONTAMINATION

Two hazards limit permissible skin contamination: (1) the external irradiation must not exceed the MPE's given in Table 4.1, (2) absorption into the body must not lead to more than the MPBB (see Appendix A). Therefore, under conditions involving regular exposure over an extended period of time, it is recommended that the permissible fixed skin contamination level of unidentifiable radioactive material should not exceed 0.5 mrad/hr beta-gamma or 20 d/m/cm<sup>2</sup> alpha (see Volume III, Appendix B). However, SKIN CONTAMINATION SHOULD ALWAYS BE REDUCED TO THE MINIMUM LEVEL POSSIBLE WITHOUT INJURY TO THE SKIN SURFACE.

TABLE 4.5

**MAXIMUM PERMISSIBLE LEVELS OF  
RADIOACTIVE ISOTOPES IN THE BODY AND EXCRETA**

| Radio-<br>element,<br>soluble<br>form | Body<br>Burden<br>( $\mu$ c) | Estimated %Dose<br>Retained at 6 months                                                                                                                                                                                                                                                                                       |      |     | Data on Urine and Feces at 6 Months |            |                                                                                                            | Ref. |
|---------------------------------------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|-----|-------------------------------------|------------|------------------------------------------------------------------------------------------------------------|------|
|                                       |                              |                                                                                                                                                                                                                                                                                                                               |      |     | Urine<br>Feces<br>(Not Critical)    | Ratio<br>% | total body content<br>eliminated in daily<br>urine.<br>d/m per 1500 cc<br>equivalent to<br>one body burden |      |
| Ac <sup>227</sup>                     | 0.03                         | 35                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/20                                | 0.01       | 7                                                                                                          | 6    |
| Am <sup>241</sup>                     | 0.05                         | 35                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/15                                | 0.005      | 5                                                                                                          | 6    |
| C <sup>14</sup>                       | 300                          | 1                                                                                                                                                                                                                                                                                                                             | 1    | 1   | 1/1                                 | 0.01       | 10 <sup>5</sup>                                                                                            | 6    |
| Ca <sup>45</sup>                      | 30                           | 50                                                                                                                                                                                                                                                                                                                            | 15   | 50  | 1/10                                | 0.005      | 3 x 10 <sup>3</sup>                                                                                        | 6    |
| Ce <sup>144</sup>                     | 5                            | 35                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/10                                | 0.01       | 1.1 x 10 <sup>3</sup>                                                                                      | 6    |
| Cm <sup>242</sup>                     | 0.05                         | 35                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/10                                | 0.005      | 5                                                                                                          | 6    |
| H <sup>3</sup>                        | 1000                         | 50*                                                                                                                                                                                                                                                                                                                           | 50*  | 50* | 10/1*                               | 5*         | 10 <sup>8</sup> *                                                                                          | 6    |
| Pa <sup>231</sup>                     | 0.02                         | 70                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 10/1                                | 0.01       | 5                                                                                                          | 6    |
| Po <sup>210</sup>                     | 0.03                         | 25                                                                                                                                                                                                                                                                                                                            | 10   | 25  | 1/15                                | 0.02       | 14                                                                                                         | 6    |
| Pu <sup>239</sup>                     | 0.04                         | 90                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/1                                 | 0.005      | 5                                                                                                          | 6    |
| Ra <sup>226</sup>                     | 0.1                          | 10                                                                                                                                                                                                                                                                                                                            | 5    | 5   | 1/10                                | 0.01       | 22                                                                                                         | 6    |
| Th <sup>230</sup>                     | 0.05                         | 60                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/10                                | 0.01       | 11                                                                                                         | 6    |
| S <sup>35</sup>                       | 90                           | 1**                                                                                                                                                                                                                                                                                                                           | 1**  | 1** | 6/1                                 | 0.5        | 8 x 10 <sup>5</sup>                                                                                        | 6    |
| Sr <sup>89</sup>                      | 4                            | 50                                                                                                                                                                                                                                                                                                                            | 15   | 50  | 1/2                                 | 0.05       | 4 x 10 <sup>3</sup>                                                                                        | 6    |
| Sr <sup>90</sup>                      | 2                            | 50                                                                                                                                                                                                                                                                                                                            | 15   | 50  | 1/2                                 | 0.05       | 2 x 10 <sup>3</sup>                                                                                        | 6    |
| Y <sup>91</sup>                       | 5                            | 35                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/10                                | 0.01       | 1.1 x 10 <sup>3</sup>                                                                                      | 6    |
| Zr <sup>95</sup>                      | 20                           | 35                                                                                                                                                                                                                                                                                                                            | 0.05 | 20  | 1/2                                 | 0.01       | 4.6 x 10 <sup>3</sup>                                                                                      | 6    |
| Fission<br>Products                   | ---                          | If urine gives 300 d/m/1500 cc: exposure should be suspected and investigation started. Radiophysical or radiochemical studies should be made to identify radioelement.                                                                                                                                                       |      |     |                                     |            |                                                                                                            | 7    |
| U <sup>233</sup>                      | .05                          | 50 d/m/24 hour sample is considered a positive indication of enriched uranium in the body.                                                                                                                                                                                                                                    |      |     |                                     |            |                                                                                                            | 7    |
| U <sup>235</sup>                      | .03                          | 200 d/m/24 hour sample indicates need for examining working environment.                                                                                                                                                                                                                                                      |      |     |                                     |            |                                                                                                            | 7    |
| U,natural                             | .005                         | (Determined by fluorimetry) 50 $\mu$ g/L considered positive indication of material in body; 100 $\mu$ g/L indicates need for examining working environment.                                                                                                                                                                  |      |     |                                     |            |                                                                                                            | 7    |
| Pu <sup>239</sup>                     | 0.04                         | 0.2 d/m/24 hour sample should be investigated if no known acute exposure has occurred since last specimen (this value indicates no more than 1/5 body burden regardless of method or time of exposure). 14 d/m/24 hour sample in specimen taken ~30 days after exposure indicates ~a permissible body burden (0.044 $\mu$ c). |      |     |                                     |            |                                                                                                            | 7    |

\* Data are for period 10 days after exposure

\*\* Data are for period one week after exposure

# MPL'S FOR AREA, EQUIPMENT, AND CLOTHING CONTAMINATION

Having set the limits for acceptable exposures, external and internal, we have now to consider how to manage surface contaminations lest they lead to unacceptable exposures. We define three levels by order of magnitude: (1) for FINAL CLEARANCE there must be no significant radiological hazard, (2) for STANDARD CLEARANCE the hazard must be amenable to ordinary operational control, (3) for OPERATIONAL CLEARANCE the control of the hazard requires special rad-safe precautions including restrictions on persons and their working times.

Surface contamination is first measured by the exposure rate above it. The MPL's for unidentified mixtures of radioactive isotopes for FINAL and STANDARD CLEARANCE are given in Tables 4.6 and 4.7. Fig. 4.1 defines FINAL, STANDARD and OPERATIONAL CLEARANCE. Volume III, Appendix B, presents the basis for the MPL's. In the main, these Final Clearance MPL's will comply with 10 CFR, Part 20, i.e., not to exceed any of the following: (1) 1/10 the yearly MPE; (2) a dose rate of 2 mr/hr or 4 mrad/hr\*, or a dose of 100 mr or 200 mrad\* per seven consecutive days; (3) the non-occupational aerosol MPC for the most restrictive  $\beta$  emitter ( $\text{Sr}^{90}$ ) and  $\alpha$  emitters (natural thorium in bones) ultimately accumulated.

STANDARD CLEARANCE is based on not exceeding any of the following: (1) the yearly MPE (5r or 10 rad\*); (2) the occupational aerosol for the most restrictive  $\beta$  emitter ( $\text{Sr}^{90}$ ) and  $\alpha$  emitter ( $\text{Pu}^{239}$ ); (3) the most restrictive body burden for  $\beta$  emitters ( $\text{Sr}^{90}$ ) and  $\alpha$  emitters (natural thorium in bones) ultimately accumulated. (OPERATIONAL CLEARANCE is required for any area where the exposure or contamination levels are in excess of STANDARD CLEARANCE.)

The recommended MPL's for OPERATIONAL CLEARANCE are discussed on Page 209.

Note that the MPL's for FINAL CLEARANCE (Table 4.6) are only a few times natural background, in fact, lower than natural background in some inhabited regions. This means "practically no detectable activity" as standard radiacs are used in the field.

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\*Penetrating exposure in r, skin dose in rads.

TABLE 4.6

**FINAL CLEARANCE**  
**MPL'S FOR UNIDENTIFIED RADIOACTIVE MATERIALS**

| Radiation             | Unit of Measurement | Area, Equipment, Personnel and Clothing |
|-----------------------|---------------------|-----------------------------------------|
| Gamma at contact      | mr/hr               | 0.05                                    |
| Beta at contact       | mrad/hr             | 0.1                                     |
| Alpha at contact      | d/m/cm <sup>2</sup> | 2*                                      |
| Beta-gamma at contact | mrad/hr             | 0.1**                                   |

\* Total amount of radioactive material should not exceed 10 times the maximum permissible body burden (MPBB) for any single release of equipment or clothing.

\*\* Not to include more than 0.05 mr/hr of  $\gamma$ .

TABLE 4.7

**STANDARD CLEARANCE**  
**MPL'S FOR UNIDENTIFIED RADIOACTIVE MATERIALS**

| Radiation             | Unit of Measurement | For Area | For Equipment | For Skin Contamination | For Clothing |      |
|-----------------------|---------------------|----------|---------------|------------------------|--------------|------|
|                       |                     |          |               |                        | Personal     | Work |
| Gamma at 3 ft         | mr/hr               | 2.5      | 2.5           | -                      | -            | -    |
| Beta-gamma at contact | mrad/hr             | 5*       | 5*            | 0.5                    | 0.5          | 1    |
| Removable beta-gamma  | d/m/cm <sup>2</sup> | 350**    | 350**         | -                      | -            | -    |
| Alpha                 | d/m/cm <sup>2</sup> | 60       | 60            | 20                     | 20.          | 60   |
| Removable alpha       | d/m/cm <sup>2</sup> | 20**     | 20**          | -                      | -            | -    |

\* Not to include more than 2.5 mr/hr of  $\gamma$ .

\*\* Total activity removable. Assuming that a wipe takes up to 10% of what is removable, the limit for the activity measured on the wipe for each cm<sup>2</sup> wiped is 35 d/m for  $\beta$ - $\gamma$  and 2 d/m for  $\alpha$ . When 100 cm<sup>2</sup> are wiped, the maximum activity allowable on the wipe is 3500 d/m for  $\beta$ - $\gamma$ ; 200 d/m for  $\alpha$ .

NOTE: A large surface with uniform 1 Mev gamma contamination of 400 d/m per cm<sup>2</sup> will measure 0.05 mr/hr close to it and 35,000 d/m per cm<sup>2</sup> will measure 2.5 mr/hr at 3 feet. For beta contamination of 1 Mev (mean energy), 35 d/m/per cm<sup>2</sup> will give 0.1 mrad/hr at contact and 2000 d/m per cm<sup>2</sup> will give 5 mrad/hr at contact.

For known alpha emitters, the  $2 \text{ d/m/cm}^2$  MPL may be increased by the ratio of the known emitters MPBB to that of natural thorium ( $0.01 \mu\text{c}$ ). However, the total amount of alpha emitters released at any one time should not exceed 10 body burdens of the isotope involved. This limitation is recommended to prevent an absorption or ingestion hazard and to minimize the hazard of concentrating the alpha emitters which may occur in some industrial processes such as laundering or smelting.

For any single contaminant of known decay rate, the MPL for FINAL CLEARANCE can be adjusted accordingly, as shown in Table 4.8. Part A is based upon strict compliance with 10 CFR, Part 20, i.e., not exceeding the specified dose rate and accumulated weekly, quarterly and yearly doses. Part B is based only upon the accumulated total dose of 0.5 r or 1.0 rad in a year.

TABLE 4.8

FINAL CLEARANCE DOSE RATES BASED ON COMPLIANCE WITH 10 CFR, PART 20, OR A YEARLY DOSE OF 0.5 r OR 1.0 RAD

| $T_{1/2}$ (Hours)                             | PART A<br>Compliance with 10 CFR,<br>Part 20 |                          |                             | PART B<br>Yearly Dose of 0.5 r or<br>1.0 rad |                          |                             |
|-----------------------------------------------|----------------------------------------------|--------------------------|-----------------------------|----------------------------------------------|--------------------------|-----------------------------|
|                                               | Factor                                       | Dose Rate at<br>Contact* |                             | Factor                                       | Dose Rate at<br>Contact* |                             |
|                                               |                                              | Gamma<br>(mr/hr)         | Beta-<br>Gamma<br>(mrad/hr) |                                              | Gamma<br>(mr/hr)         | Beta-<br>Gamma<br>(mrad/hr) |
| $\leq 35$                                     | 40                                           | 2.0                      | 4.0                         | 190                                          | 9.5                      | 19.0                        |
| $>35$ but $\leq 80$                           | 20                                           | 1.0                      | 2.0                         | 90                                           | 4.5                      | 9.0                         |
| $>80$ but $\leq 150$                          | 10                                           | 0.5                      | 1.0                         | 40                                           | 2.0                      | 4.0                         |
| $>150$ but $\leq 1.7 \times 10^3$             | 1                                            | 0.05                     | 0.1                         | 4                                            | 0.2                      | 0.4                         |
| $>1.7 \times 10^3$ but $\leq 4.8 \times 10^3$ | -                                            | -                        | -                           | 2                                            | 0.1                      | 0.2                         |

\* Penetrating exposure in r, skin dose in rads

The recommended Standard Clearance MPL's for personnel and clothing will be noted to be as much as a factor of 10 above those for FINAL CLEARANCE. In view of the small number of persons who might become contaminated to this degree, it is felt that Standard Clearance MPL's for personnel and personal clothing need not be based on damage to the genetic pool (Final Clearance criteria). The contamination levels recommended are not statutory limits, but are intended to be used as GUIDELINES when such circumstances are encountered.

The recommended MPL's for contamination control under STANDARD CLEARANCE are not an indication of biological damage but an index to the degree of successful administrative control on the use of radiation sources and the movement of radioactive material in a restricted area. An adequate rad-safe program should be capable of maintaining radiation exposures and contamination levels at or below the recommended MPL's.

Exposure to be permitted must always be balanced against the importance of the operation and the mission. RADIOLOGICAL EXPOSURE MUST ALWAYS BE HELD TO A PRACTICAL MINIMUM. CONTAMINATION SHOULD ALWAYS BE REMOVED AS COMPLETELY AS POSSIBLE. Some definite minimum must be established as acceptable so as not to force expenditure of money and effort in trying to remove something which cannot produce detectable damage.

Serious personnel hazards may arise from contamination levels greater than those recommended for controlled use and require special evaluation by competent personnel (health physicists). The radiological hazards are minimal if they are within the limits recommended for controlled use and should not present a difficult contamination control problem. Levels recommended for FINAL CLEARANCE (general release) define a condition of essentially no radiological hazard to personnel. However, even though the Final and Standard Clearance MPL's present no radiological hazard to personnel, laboratory or industrial operations may require more stringent control limits.

## **FINAL CLEARANCE (UNCONTROLLED RELEASE)**

If the radiological situation is such that the radiation or contamination level will not produce exposure to personnel in excess of 10 % of the MPL's for operations in restricted areas (STANDARD CLEARANCE), then the area or material may be released for uncontrolled use.<sup>1</sup> This radiological condition suitable for general release will be called FINAL CLEARANCE. Table 4.6 presents the MPL's for unidentified radioisotopes. There is no qualification on the stability of the contamination. Even if it were all removable, there would be no hazard. However, in cases of large equipment, great numbers of small units, or large quantities of clothing, the total alpha activity for any single release should not exceed 10 times the MPBB for the radioisotope involved. Also, operations which produce aerosols (grinding or wire



brushing) or might concentrate contamination (laundering) should be controlled so as not to produce contamination levels greater than the MPC's for aerosol or water listed in Appendix A.

**SALVAGE OR SCRAP** Equipment or portions thereof released for salvage or scrap with contamination below FINAL CLEARANCE may, in time, constitute an industrial nuisance. An example of such a nuisance is the fogging of photographic film caused by paper made from contaminated pulp. Moreover, such scrap will increase the background counting rate of any radiation detector in which or near which it is used.

In releasing scrap with any measurable contamination at all, it should be made reasonably sure that the material will not be used in connection with future radiation measurements. The contamination level should be measured and a record of the kind and amount of radioactivity given to anyone taking the material.

### **STANDARD CLEARANCE (FOR UNRESTRICTED AREAS WITHIN A RESTRICTED AREA FOR 40 HR/WK)**

The radiation and contamination levels are such that no person will exceed the MPE and MPC in a 40 hour week while carrying on his normal duties. After STANDARD CLEARANCE is achieved, it is unnecessary to impose any radiological controls on the activities of the personnel or movement of equipment except that personnel and equipment will remain under the control of a radiological safety officer within restricted areas. Table 4.7 presents the MPL's for unidentified radioisotopes with a qualification on removable activity for equipment and areas.

**MIXED FISSION PRODUCT CONTAMINATION** The permissible levels of contamination with mixed fission products for release to unrestricted areas depends on the age of the fission products and their source. Fission products from a weapon detonation approximately follow the  $t^{-1.2}$  decay, whereas fission products from reactor operations will have a longer apparent half-life due to the build-up of the longer-lived isotopes. The Final and Standard Clearance values stated in Tables 4.6 and 4.7 are recommended for mixed fission products produced from the long-time operation of a reactor.

For products released early in the life of a reactor core or from nuclear explosions, the exposure rate for clearance can be based on the predictable year's accumulative dose, according to the age of the fission products. The graphs<sup>9</sup> in Fig. 4.2 show how high the exposure rate can be for a given age of mixed fission products and still keep within the proper limits of surface dose, namely, not to exceed 2 mrad/hr (specified in 10 CFR, 20) or 1.0 rad in a year of continuous (168 hr/wk) exposure for FINAL CLEARANCE, and for STANDARD CLEARANCE not to exceed 0.3 rad/wk or 6 rad/quarter or 10 rad/yr (based on a 40 hr/wk exposure).

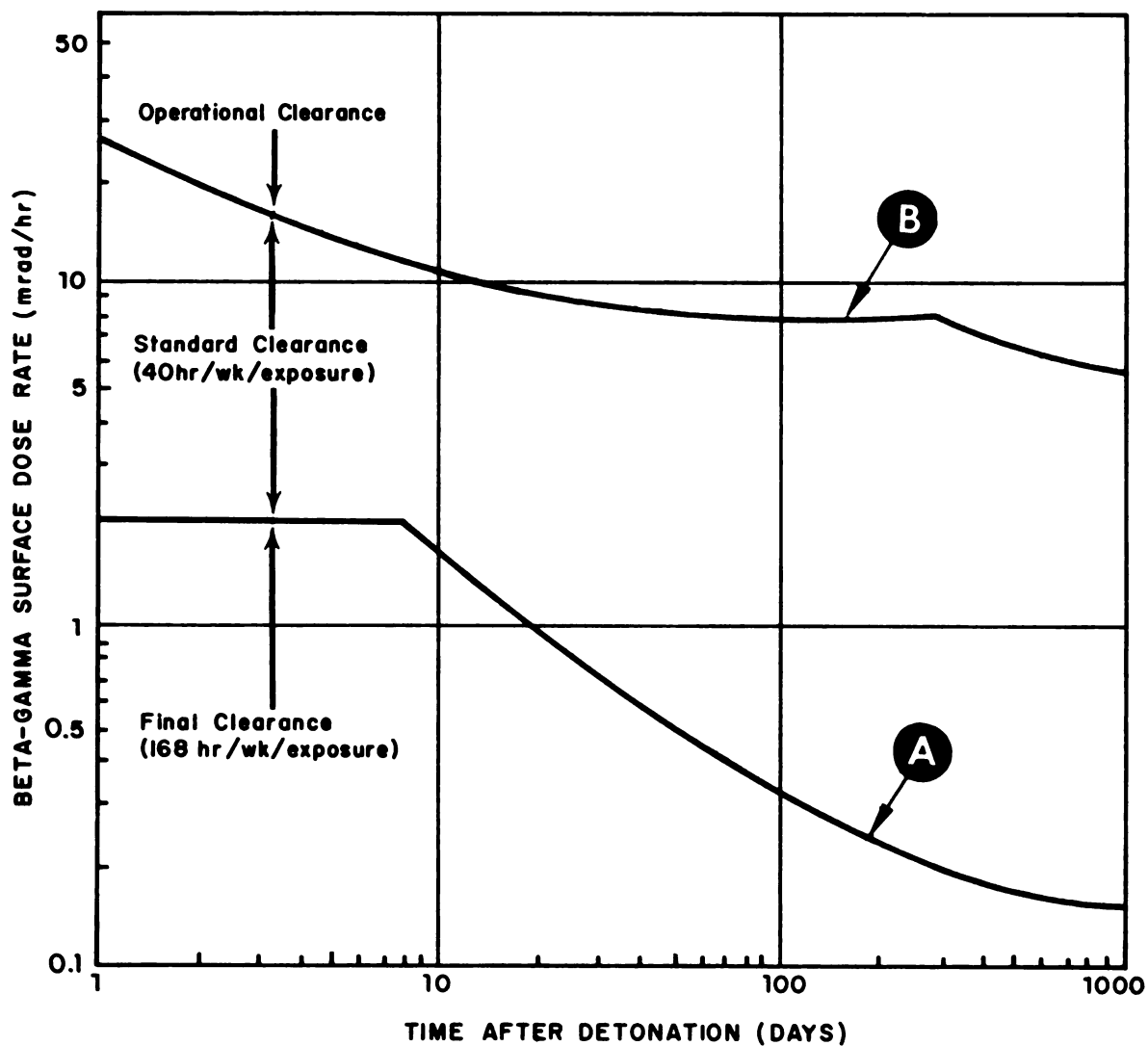


FIG. 4.2 FINAL, STANDARD AND OPERATIONAL CLEARANCE CONTAMINATION LEVELS RECOMMENDED FOR NUCLEAR WEAPON FISSION-PRODUCT CONTAMINATED EQUIPMENT.

For exposure times greater than 40 hr/wk, the permissible levels for clearance are lower in proportion. When exposure is to be limited to half a year, however, the permissible exposure rate may not be doubled. (For young fission products, almost all the exposure occurs in the first few months.)

Contamination levels above Curve B (Operational Clearance Levels) require radiological controls (limitation of exposure time, etc.) which should be adjusted to the radiation levels newly determined from time to time. Between Curves A and B, unnecessary exposure must be prevented. Radiological controls are not needed for those occupationally exposed up to 40 hr/wk, if removable contamination does not exceed 10% of curve B.

The same principle of setting present permissible levels according to predicted future accumulated dose can be applied to aerosols. The curves<sup>10</sup> in Fig. 4.3 show the fission-product activity which inhaled continuously 24 hrs/day for various lengths of time, will just give the maximum accumulated dose permitted in 90 days. (There are two sets of curves; one for occupational exposure and one for general population.) Ninety days would seem to be ample time for most recovery operations. Also, if the period of exposure is less than 168 hrs/wk, the MPC can be proportionally increased.

If contamination is blowing in from a distance, the aerosol may be the controlling hazard. But if the aerosol arises from resuspension of contamination under foot, the external gamma exposure will keep people out, even though the aerosol might not require respirators. This is obvious from the scales at the right side of Fig. 4.3, which show the associated  $\gamma$  dose rate at 3 feet and the ground contamination which might resuspend to give the aerosol levels plotted (calculated from resuspension factor  $4 \times 10^{-8} (\mu\text{c}/\text{cm}^3)/(\mu\text{c}/\text{cm}^2)$  as in Appendix B, Volume III).

Food and water may become contaminated with fission products (degree of segregation unknown). Fig. 4.4 presents the MPC's, according to age since fission, for various durations of continuous exposure, based on 0.3 rem to the critical organ in 90 days.

#### **MPC'S FOR AIR AND WATER CONTAMINATION BY KNOWN ISOTOPES**

Table I of Appendix A lists the MPC's for specific radioisotopes in aerosol form which will not lead to more than the MPBB in a 40 hr/wk exposure. If the exposure time is shorter, the MPC is obviously higher in proportion. For longer times or higher concentrations, respirators must be worn. Table II of Appendix A gives the MPC's for continuous exposure (168 hr/wk on the basis of the same MPBB (occupational exposure)). These limits are lowered to 1/10 for the population at large.

The similar pertinent MPC's for known radioisotopes in food and water are given in the same tables.

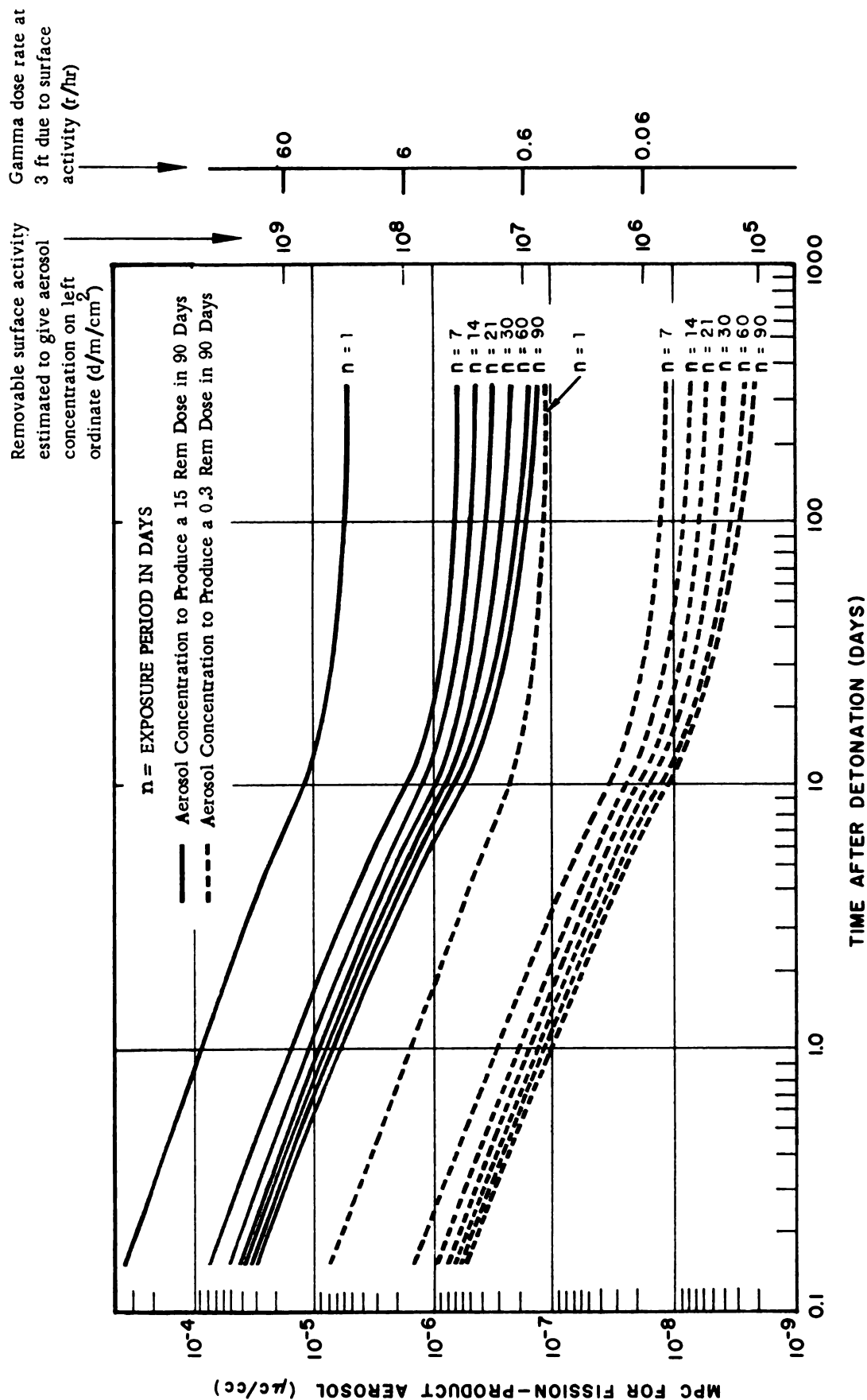


FIG. 4.3 MAXIMUM PERMISSIBLE CONCENTRATION OF FISSION PRODUCTS IN AIR VS AGE OF FISSION PRODUCTS AND EXPOSURE TIME TO PRODUCE A 15 REM AND 0.3 REM DOSE IN 90 DAYS TO THE CRITICAL ORGAN.

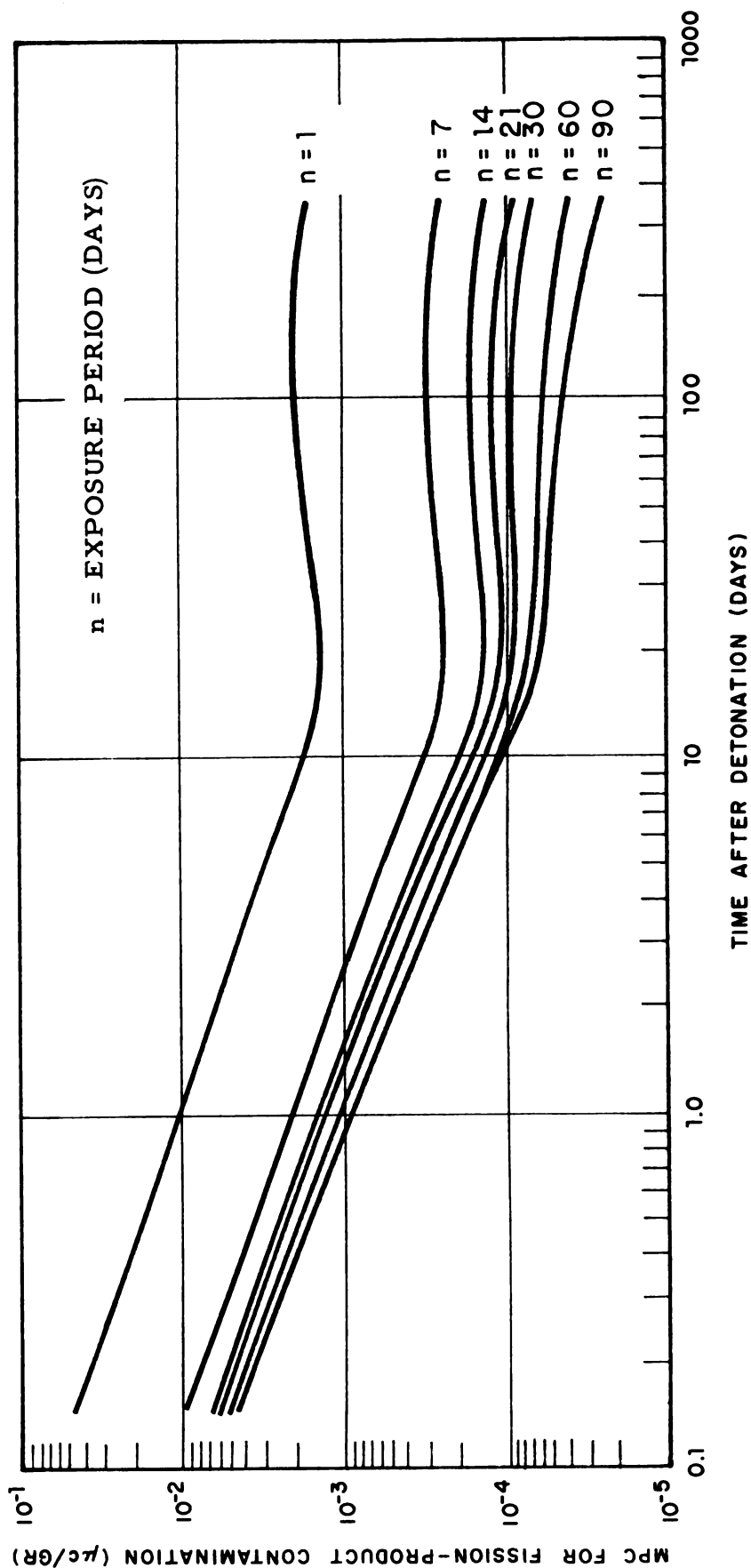


FIG. 4.4 MAXIMUM PERMISSIBLE CONCENTRATION OF FISSION PRODUCTS IN FOOD AND WATER VS AGE OF FISSION PRODUCTS AND EXPOSURE TIME TO PRODUCE A 0.3 REM DOSE IN 90 DAYS TO THE CRITICAL ORGAN

**PLUTONIUM CONTAMINATION** Plutonium, an alpha emitter, produces a biological hazard when taken into the body. The modes of entry into the body are ingestion, inhalation, and absorption through breaks in the skin surface. The primary radiological problem is the inhalation of plutonium-contaminated air since absorption from the intestines is extremely small compared to absorption from the lungs. (Approximately 0.003% of the ingested amount is absorbed from the intestines, compared to 2 to 10% of the inhaled amount from the lungs.) Fig. 4.5 presents the aerosol MPC for plutonium based on the MPBB of 0.5  $\mu\text{g}$ . It is to be noted that the lung is the critical organ for exposure times of less than four years, after which the skeleton becomes the critical organ.

Fig. 4.6 is an extension of Fig. 4.5, relating the removable surface contamination hazard to the aerosol hazard. The same assumptions used for estimating the resuspension of fission-product surface contamination apply. Fig. 4.6 allows an estimate of the potential aerosol hazard when time does not permit an analysis of a filtered aerosol sample. (The analysis of an alpha aerosol sample usually requires a 24 hour decay to correct for the content of natural thoron daughters in the air.) The expected instrument readings of some alpha radiacs are also given for various surface contamination levels. For example, if a 10 hour job were to be performed in a plutonium-contaminated area of 100  $\mu\text{g}/\text{m}^2$  surface activity (reading of 20 K c/m on the Eberline PAC 3-G alpha radiac), no respiratory protection would be required.

## **OPERATIONAL CLEARANCE (MPL'S FOR SPECIAL OPERATIONS)**

The MPE's and MPC's discussed in previous sections of this Chapter present levels of radiation and radioactive contamination for normal work in a controlled area involving radioactivity or radiation sources. As more knowledge is gained about the biological and genetic effects of ionizing radiation, the presently accepted values for MPE and MPC will no doubt be amended.

Following any type of accident in which radioactivity is involved, one of the first questions posed is: under what conditions, if any, can the area and equipment be occupied or used. To establish radiological clearance, the radiation and contamination levels must be determined by persons with knowledge and training in the field of radiological safety, using adequate monitoring equipment.

Chapter 3 of this Volume sets forth monitoring techniques needed for making a gross and/or detailed evaluation of any radiation and/or contamination situation.

There are operations and situations that are of brief duration or are expected but rarely (may occur only once) in which exposure rates are above those permitted for normal operations. Examples are: Field tests

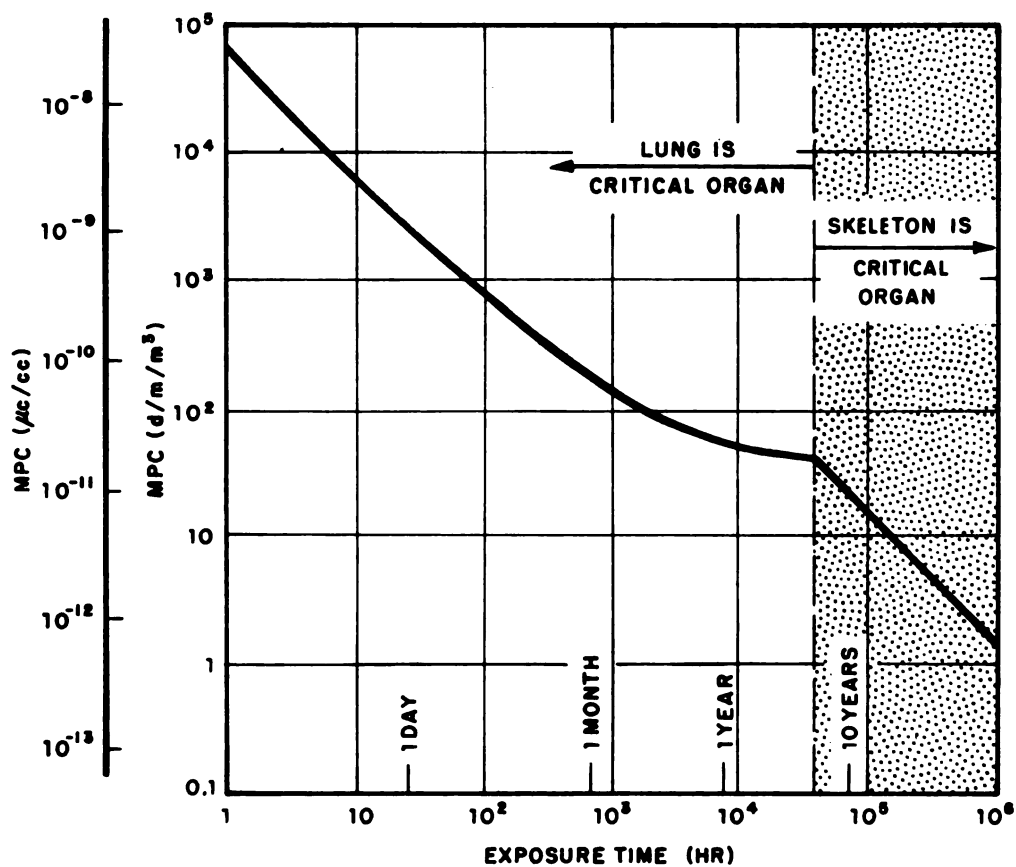


FIG. 4.5 PLUTONIUM AEROSOL MPC BASED ON MPBB OF 0.5  $\mu\text{g}$ .

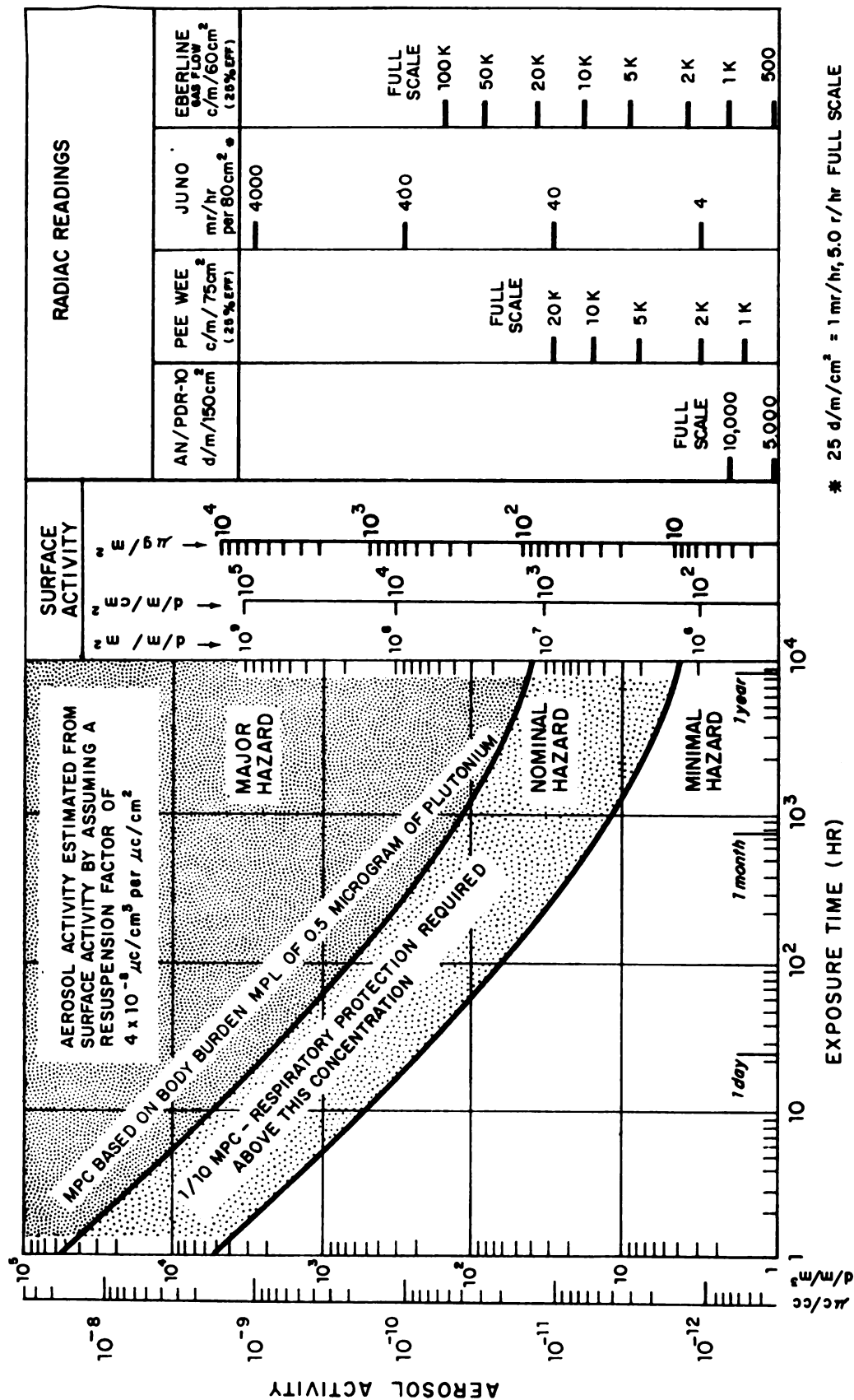


FIG. 4.6 MAXIMUM PERMISSIBLE CONCENTRATION OF PLUTONIUM IN AIR CORRELATED WITH SURFACE ACTIVITY AND RADIAC READINGS.



of nuclear devices, special work in restricted areas, emergency situations such as radiological accidents and fires involving radioactivity. Whatever is done in such cases is called a SPECIAL OPERATION. In order to permit designated persons to receive the year's MPD in a short time or to draw on the long-time limit of  $(N-18) \cdot 5$  rem, measurements, precautions and controls especially adapted to the particular situation are necessary.

An OPERATIONAL CLEARANCE implies a real or potential radiological hazard that can be met only in a SPECIAL OPERATION and must state the particular controls necessary to maintain health and safety. The guidelines for an OPERATIONAL CLEARANCE are based on the MPE and MPC levels for STANDARD CLEARANCE. Radiological situations range from low-level contamination, such as an industrial or operational nuisance, through medium and high levels, which require varying degrees of control. It is obvious that an OPERATIONAL CLEARANCE covers a broad range of radiological problems. A precise description of the radiological situation must be made, along with the necessary precautions required (protective clothing, shielding, stay-times, etc.) to eliminate or minimize the hazard to personnel. An OPERATIONAL CLEARANCE establishes the fact that a real or potential radiological hazard exists. Only when the proper controls are initiated is it safe to go ahead with the job at hand.

**MPE'S FOR EXTERNAL EXPOSURE** For OPERATIONAL CLEARANCE, the MPE's are set according to the yearly MPD's listed in Table 4.1. THE OPERATIONAL MPE MAY BE RECEIVED IN A SINGLE DOSE. The doses listed are well below the threshold of perceptible bodily effect. It is clear, for example, that the acute local irradiation in a routine gastrointestinal series, which may be as much as 40 r to a highly sensitive area, is not dangerous. Unnecessary exposure is, however, not to be permitted. EXPOSURE TO IONIZING RADIATION SHOULD ALWAYS BE KEPT TO A MINIMUM. The MPE's and MPC's recommended in this section are values which will permit operations to be conducted in a restricted area without doing any harm to the personnel exposed.

► The MPE for any radiation with a half-value layer greater than 1 mm of soft tissue (DEEP DOSE) is 12 rem whole body-exposure in any one year. However, the maximum permissible accumulated dose (MPD), namely,  $(N-18) \cdot 5$  rem, must not be exceeded. If a person's occupational exposure is documented, he may be permitted to draw on his reserve exposure up to 12 rem in a year. IF THE PREVIOUS EXPOSURE OF THE PERSON IS NOT KNOWN, EXPOSURE IN THE SPECIAL OPERATION MUST BE LIMITED TO 5 REM FOR THE YEAR. When an individual accumulates 12 rem, he must be removed from exposure to radiation for the ensuing year. Additional exposure to radiation after the year has elapsed will be governed by his long-time MPD.

▶ The MPE for any radiation with a half-value layer less than 1 mm of soft tissue (SURFACE DOSE) is 24 rem to the skin of the whole body in any one year, but not to exceed the MPD for long-time accumulation, namely, (N-18)·10 rem. Stipulations in regard to control of the MPD are the same as outlined for DEEP DOSE.

▶ The MPE for the extremities, whatever the half-value layer, is 100 rem to hands and wrists or to feet and ankles, but not to exceed the MPD for long-time accumulation, namely, (N-18)·75 rem. Stipulations in regard to control of the MPD are the same as outlined for DEEP DOSE.

▶ **MEDICAL AND EMERGENCY EXPOSURES.** No MPD is established for the intentional exposure of patients to radiation for the purpose of medical diagnosis or medical therapy.<sup>1, 2, 3</sup> Such irradiations shall be accepted as necessary for the persons own well-being and arbitrarily ignored in continuing the individual's work under the occupational MPD of (N-18)·5 rem. NBS 69 containing the recommendations of the National Committee on Radiation Protection states that: "An accidental or emergency dose of 25 rem to the whole body or major portion thereof, occurring only once in the lifetime of the person, need not be included in the determination of the radiation exposure status of that person."<sup>2, 3</sup>

When an emergency or accidental exposure of 25 rem or less occurs, the dose received should be made a part of the individual's radiation exposure record. If practical, the exposure should be amortized over an appropriate time period, but the individual involved should not be removed from his normal occupational exposure even if the exposure received causes his MPD to exceed (N-18)·5 rem.

In either case, it is proper for the person to accept the effect of the medical or emergency exposure for whatever it amounts to and arbitrarily ignore it in continuing under the occupational MPD of (N-18)·5 rem. This assures that his occupational exposure will not do him any further injury. It should be recognized that the effects from exposures even many times the MPD's which have been adopted are entirely unobservable, even though we are unwilling at present to reduce the factor of safety.

## **MPL'S FOR CONTAMINATION OF PERSONNEL, EQUIPMENT AND CLOTHING**

Account must be taken of both external irradiation and possible internal contamination particularly if a large percentage of the contamination is removable. The dose from both sources must be kept below the MPD. The MPC's for air and water must be set so that the dose from both external and internal irradiation does not exceed the Operational MPE for External Exposure. The MPL's for contamination control under OPERATIONAL CLEARANCE are therefore set at levels that make the problem manageable. The recommended values are 10 times the MPL's for STANDARD CLEARANCE. Contaminations above these levels require special management under advice of a health physicist.

# RECORDS OF EXPOSURES

It is necessary to keep records of:

- ① The exposure of every person at all likely to receive a total-body exposure above 50 mrem in a week, or who enters an area where a major part of his body might be exposed to 100 mrem in an hour.
- ② Internal contamination measured, estimated or suspected, above the MPBB's listed in Table III of Appendix A.
- ③ Durations of exposure to air or water contaminated above the MPC's listed in Tables I and II of Appendix A.
- ④ The results of radioactivity assays on the body or body products (urine, stool, breath)

A suggested form for record purposes is shown in Chapter 3 of this Volume. Every individual should be notified annually of his exposure for the previous year, and his long-time exposure reserve. For most operations, it is good practice to inform individuals of their exposure if it approaches the administrative MPE or exceeds the exposure established for a particular operation.

Where radioactive materials subject to AEC license are present, the Standard for Protection Against Radiations, Federal Register, Title 10, Part 20, sets forth requirements for notification of exposure above certain limits and in cases of accidental release of radioactive materials.

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2. National Bureau of Standards Handbook No. 69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposures." 5 June 1959.
3. National Bureau of Standards Handbook No. 59, "Permissible Dose from External Sources of Ionizing Radiation," with Addendum, 8 January 1957, Maximum Permissible Exposures to Man. (A preliminary statement of the National Committee on Radiation Protection and Measurements), and with Addendum, 15 April 1958, Maximum Permissible Radiation Exposures to Man.
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# Rad-Safe is assessment delineation and control

of the radiological situation to minimize external exposure and internal contamination of personnel from ionizing radiations and radioactive material.

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**(PORACC)**

# MAXIMUM PERMISSIBLE CONCENTRATIONS IN WATER AND AIR ABOVE NATURAL BACKGROUND\*

| ELEMENT<br>(atomic number) | ISOTOPE <sup>1</sup> | TABLE I <sup>3</sup>               |                                  | TABLE II <sup>4,5</sup>            |                                  | TABLE III<br>MPBB <sup>6</sup><br>(body burden)<br>( $\mu$ c) |
|----------------------------|----------------------|------------------------------------|----------------------------------|------------------------------------|----------------------------------|---------------------------------------------------------------|
|                            |                      | Column 1<br>WATER<br>( $\mu$ c/cc) | Column 2<br>AIR<br>( $\mu$ c/cc) | Column 1<br>WATER<br>( $\mu$ c/cc) | Column 2<br>AIR<br>( $\mu$ c/cc) |                                                               |
| Actinium<br>(89)           | Ac 227 S             | $6 \times 10^{-3}$                 | $3 \times 10^{-12}$              | $2 \times 10^{-3}$                 | $8 \times 10^{-13}$              | 0.03                                                          |
|                            | I                    | $9 \times 10^{-4}$                 | $3 \times 10^{-11}$              | $3 \times 10^{-3}$                 | $9 \times 10^{-12}$              | -                                                             |
| Ac 228 S                   |                      | $3 \times 10^{-3}$                 | $8 \times 10^{-9}$               | $9 \times 10^{-4}$                 | $3 \times 10^{-8}$               | 0.04                                                          |
|                            | I                    | $3 \times 10^{-3}$                 | $2 \times 10^{-8}$               | $9 \times 10^{-4}$                 | $6 \times 10^{-9}$               | -                                                             |
| Americium<br>(95)          | Am 241 S             | $1 \times 10^{-4}$                 | $6 \times 10^{-12}$              | $4 \times 10^{-5}$                 | $2 \times 10^{-12}$              | 0.05                                                          |
|                            | I                    | $8 \times 10^{-4}$                 | $1 \times 10^{-10}$              | $2 \times 10^{-4}$                 | $4 \times 10^{-11}$              | -                                                             |
| Am 243 S                   |                      | $1 \times 10^{-4}$                 | $6 \times 10^{-12}$              | $4 \times 10^{-5}$                 | $2 \times 10^{-12}$              | 0.05                                                          |
|                            | I                    | $8 \times 10^{-4}$                 | $1 \times 10^{-10}$              | $3 \times 10^{-4}$                 | $4 \times 10^{-11}$              | -                                                             |
| Antimony<br>(51)           | Sb 122 S             | $8 \times 10^{-4}$                 | $2 \times 10^{-7}$               | $3 \times 10^{-4}$                 | $6 \times 10^{-8}$               | 20                                                            |
|                            | I                    | $8 \times 10^{-4}$                 | $1 \times 10^{-7}$               | $3 \times 10^{-4}$                 | $5 \times 10^{-8}$               | -                                                             |
| Sb 124 S                   |                      | $7 \times 10^{-4}$                 | $2 \times 10^{-7}$               | $2 \times 10^{-4}$                 | $5 \times 10^{-8}$               | 10                                                            |
|                            | I                    | $7 \times 10^{-4}$                 | $2 \times 10^{-8}$               | $2 \times 10^{-4}$                 | $7 \times 10^{-9}$               | -                                                             |
| Sb 125 S                   |                      | $3 \times 10^{-3}$                 | $5 \times 10^{-7}$               | $1 \times 10^{-3}$                 | $2 \times 10^{-7}$               | 40                                                            |
|                            | I                    | $3 \times 10^{-3}$                 | $3 \times 10^{-8}$               | $1 \times 10^{-3}$                 | $9 \times 10^{-9}$               | -                                                             |
| Argon <sup>2</sup><br>(18) | A 37 Sub             | -                                  | $6 \times 10^{-3}$               | -                                  | $1 \times 10^{-3}$               | -                                                             |
|                            | A 41 Sub             | -                                  | $2 \times 10^{-4}$               | -                                  | $4 \times 10^{-7}$               | -                                                             |
| Arsenic<br>(33)            | As 73 S              | $1 \times 10^{-2}$                 | $2 \times 10^{-6}$               | $5 \times 10^{-3}$                 | $7 \times 10^{-7}$               | 300                                                           |
|                            | I                    | $1 \times 10^{-2}$                 | $4 \times 10^{-7}$               | $5 \times 10^{-3}$                 | $1 \times 10^{-7}$               | -                                                             |
| As 74 S                    |                      | $2 \times 10^{-3}$                 | $3 \times 10^{-7}$               | $5 \times 10^{-4}$                 | $1 \times 10^{-7}$               | 40                                                            |
|                            | I                    | $2 \times 10^{-3}$                 | $1 \times 10^{-7}$               | $5 \times 10^{-4}$                 | $4 \times 10^{-8}$               | -                                                             |
| As 76 S                    |                      | $6 \times 10^{-4}$                 | $1 \times 10^{-7}$               | $2 \times 10^{-4}$                 | $4 \times 10^{-8}$               | 20                                                            |
|                            | I                    | $6 \times 10^{-4}$                 | $1 \times 10^{-7}$               | $2 \times 10^{-4}$                 | $3 \times 10^{-8}$               | -                                                             |
| As 77 S                    |                      | $2 \times 10^{-3}$                 | $5 \times 10^{-7}$               | $8 \times 10^{-4}$                 | $2 \times 10^{-7}$               | 80                                                            |
|                            | I                    | $2 \times 10^{-3}$                 | $4 \times 10^{-7}$               | $8 \times 10^{-4}$                 | $1 \times 10^{-7}$               | -                                                             |
| Astatine<br>(85)           | At 211 S             | $5 \times 10^{-3}$                 | $7 \times 10^{-9}$               | $2 \times 10^{-3}$                 | $2 \times 10^{-9}$               | 0.02                                                          |
|                            | I                    | $2 \times 10^{-3}$                 | $3 \times 10^{-9}$               | $7 \times 10^{-4}$                 | $1 \times 10^{-9}$               | -                                                             |
| Barium<br>(56)             | Ba 131 S             | $5 \times 10^{-3}$                 | $1 \times 10^{-6}$               | $2 \times 10^{-3}$                 | $4 \times 10^{-7}$               | 50                                                            |
|                            | I                    | $5 \times 10^{-3}$                 | $4 \times 10^{-7}$               | $2 \times 10^{-3}$                 | $1 \times 10^{-7}$               | -                                                             |
| Ba 140 S                   |                      | $8 \times 10^{-4}$                 | $1 \times 10^{-7}$               | $3 \times 10^{-4}$                 | $4 \times 10^{-8}$               | 4                                                             |
|                            | I                    | $7 \times 10^{-4}$                 | $4 \times 10^{-8}$               | $2 \times 10^{-4}$                 | $1 \times 10^{-8}$               | -                                                             |
| Berkelium<br>(97)          | Bk 249 S             | $2 \times 10^{-2}$                 | $9 \times 10^{-10}$              | $6 \times 10^{-3}$                 | $3 \times 10^{-10}$              | 0.7                                                           |
|                            | I                    | $2 \times 10^{-2}$                 | $1 \times 10^{-7}$               | $6 \times 10^{-3}$                 | $4 \times 10^{-8}$               | -                                                             |
| Beryllium<br>(4)           | Be 7 S               | $5 \times 10^{-2}$                 | $6 \times 10^{-6}$               | $2 \times 10^{-2}$                 | $2 \times 10^{-6}$               | 600                                                           |
|                            | I                    | $5 \times 10^{-2}$                 | $1 \times 10^{-6}$               | $2 \times 10^{-2}$                 | $4 \times 10^{-7}$               | -                                                             |

\* See note at end of table.  
 1 Soluble (S); Insoluble (I); Submersion in a cloud of gaseous material (Sub).  
 2 Noble gas - Values given for submersion in an infinite cloud.  
 3 Table I based on 40 hours exposure per seven days.  
 4 Table II based on continuous exposure 168 hours per week.  
 5 For non-occupation exposure take 1/10 of values in this Table.  
 6 Maximum Permissible Body Burden (MPBB).

| TABLE I <sup>3</sup>       |                      |                  | TABLE II <sup>4,5</sup> |                       | TABLE III            |                       |      |
|----------------------------|----------------------|------------------|-------------------------|-----------------------|----------------------|-----------------------|------|
| ELEMENT<br>(atomic number) | ISOTOPE <sup>1</sup> | Column 1         | Column 2                | Column 1              |                      | Column 2              |      |
|                            |                      | WATER<br>(μc/cc) | AIR<br>(μc/cc)          | WATER<br>(μc/cc)      | AIR<br>(μc/cc)       |                       |      |
| Bismuth<br>(83)            | Bi 206               | S                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 4 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  | 1    |
|                            |                      | I                | 1 x 10 <sup>-3</sup>    | 1 x 10 <sup>-7</sup>  | 4 x 10 <sup>-4</sup> | 5 x 10 <sup>-8</sup>  |      |
|                            | Bi 207               | S                | 2 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 6 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  | 2    |
|                            |                      | I                | 2 x 10 <sup>-3</sup>    | 1 x 10 <sup>-8</sup>  | 6 x 10 <sup>-4</sup> | 5 x 10 <sup>-9</sup>  |      |
|                            | Bi 210               | S                | 1 x 10 <sup>-3</sup>    | 6 x 10 <sup>-9</sup>  | 4 x 10 <sup>-4</sup> | 2 x 10 <sup>-9</sup>  | 0.04 |
| Bromine<br>(35)            |                      | I                | 1 x 10 <sup>-3</sup>    | 6 x 10 <sup>-9</sup>  | 4 x 10 <sup>-4</sup> | 2 x 10 <sup>-9</sup>  | 0.01 |
|                            | Br 82                | S                | 1 x 10 <sup>-2</sup>    | 1 x 10 <sup>-7</sup>  | 4 x 10 <sup>-3</sup> | 3 x 10 <sup>-8</sup>  | -    |
|                            |                      | I                | 1 x 10 <sup>-2</sup>    | 2 x 10 <sup>-7</sup>  | 4 x 10 <sup>-3</sup> | 7 x 10 <sup>-8</sup>  |      |
|                            |                      | S                | 8 x 10 <sup>-3</sup>    | 1 x 10 <sup>-6</sup>  | 3 x 10 <sup>-3</sup> | 4 x 10 <sup>-7</sup>  | 10   |
| Cadmium<br>(48)            |                      | I                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 4 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  |      |
|                            | Cd 109               | S                | 5 x 10 <sup>-3</sup>    | 5 x 10 <sup>-8</sup>  | 2 x 10 <sup>-3</sup> | 2 x 10 <sup>-8</sup>  | 20   |
|                            |                      | I                | 5 x 10 <sup>-3</sup>    | 7 x 10 <sup>-8</sup>  | 2 x 10 <sup>-3</sup> | 3 x 10 <sup>-8</sup>  |      |
|                            | Cd 115m              | S                | 7 x 10 <sup>-4</sup>    | 4 x 10 <sup>-8</sup>  | 3 x 10 <sup>-4</sup> | 1 x 10 <sup>-8</sup>  | 3    |
|                            |                      | I                | 7 x 10 <sup>-4</sup>    | 4 x 10 <sup>-8</sup>  | 3 x 10 <sup>-4</sup> | 1 x 10 <sup>-8</sup>  |      |
| Calcium<br>(20)            | Cd 115               | S                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 3 x 10 <sup>-4</sup> | 8 x 10 <sup>-8</sup>  | 3    |
|                            |                      | I                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 4 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  |      |
|                            | Ca 45                | S                | 3 x 10 <sup>-4</sup>    | 3 x 10 <sup>-8</sup>  | 9 x 10 <sup>-5</sup> | 1 x 10 <sup>-8</sup>  | 30   |
|                            |                      | I                | 5 x 10 <sup>-3</sup>    | 1 x 10 <sup>-7</sup>  | 2 x 10 <sup>-3</sup> | 4 x 10 <sup>-8</sup>  |      |
| Californium<br>(98)        | Ca 47                | S                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 5 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  | 5    |
|                            |                      | I                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 3 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  |      |
|                            | Cf 249               | S                | 1 x 10 <sup>-4</sup>    | 2 x 10 <sup>-12</sup> | 4 x 10 <sup>-5</sup> | 5 x 10 <sup>-13</sup> | 0.04 |
|                            |                      | I                | 7 x 10 <sup>-4</sup>    | 1 x 10 <sup>-10</sup> | 2 x 10 <sup>-4</sup> | 3 x 10 <sup>-11</sup> |      |
|                            | Cf 250               | S                | 4 x 10 <sup>-4</sup>    | 5 x 10 <sup>-12</sup> | 1 x 10 <sup>-4</sup> | 2 x 10 <sup>-12</sup> | 0.04 |
|                            |                      | I                | 7 x 10 <sup>-4</sup>    | 1 x 10 <sup>-10</sup> | 3 x 10 <sup>-4</sup> | 3 x 10 <sup>-11</sup> |      |
|                            | Cf 252               | S                | 7 x 10 <sup>-4</sup>    | 2 x 10 <sup>-11</sup> | 2 x 10 <sup>-4</sup> | 7 x 10 <sup>-12</sup> | 0.04 |
|                            |                      | I                | 7 x 10 <sup>-4</sup>    | 1 x 10 <sup>-10</sup> | 2 x 10 <sup>-4</sup> | 4 x 10 <sup>-11</sup> |      |
| Carbon<br>(6)              | C 14                 | S                | 2 x 10 <sup>-2</sup>    | 4 x 10 <sup>-6</sup>  | 8 x 10 <sup>-3</sup> | 1 x 10 <sup>-6</sup>  | 300  |
|                            | (CO <sub>2</sub> )   | Sub              | -                       | 5 x 10 <sup>-5</sup>  | -                    | 1 x 10 <sup>-5</sup>  |      |
| Cerium<br>(58)             | Ce 141               | S                | 3 x 10 <sup>-3</sup>    | 4 x 10 <sup>-7</sup>  | 9 x 10 <sup>-4</sup> | 2 x 10 <sup>-7</sup>  | 30   |
|                            |                      | I                | 3 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 9 x 10 <sup>-4</sup> | 5 x 10 <sup>-8</sup>  |      |
|                            | Ce 143               | S                | 1 x 10 <sup>-3</sup>    | 3 x 10 <sup>-7</sup>  | 4 x 10 <sup>-4</sup> | 9 x 10 <sup>-8</sup>  | 7    |
|                            |                      | I                | 1 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 4 x 10 <sup>-4</sup> | 7 x 10 <sup>-8</sup>  |      |
|                            | Ce 144               | S                | 3 x 10 <sup>-4</sup>    | 1 x 10 <sup>-8</sup>  | 1 x 10 <sup>-4</sup> | 3 x 10 <sup>-9</sup>  | 5    |
|                            |                      | I                | 3 x 10 <sup>-4</sup>    | 6 x 10 <sup>-9</sup>  | 1 x 10 <sup>-4</sup> | 2 x 10 <sup>-9</sup>  |      |
|                            | Cs 131               | S                | 7 x 10 <sup>-2</sup>    | 1 x 10 <sup>-5</sup>  | 2 x 10 <sup>-2</sup> | 4 x 10 <sup>-6</sup>  | 700  |
|                            |                      | I                | 3 x 10 <sup>-2</sup>    | 3 x 10 <sup>-6</sup>  | 9 x 10 <sup>-3</sup> | 1 x 10 <sup>-6</sup>  |      |
| Cesium<br>(55)             | Cs 134m              | S                | 2 x 10 <sup>-1</sup>    | 4 x 10 <sup>-5</sup>  | 6 x 10 <sup>-2</sup> | 2 x 10 <sup>-6</sup>  | 100  |
|                            |                      | I                | 3 x 10 <sup>-4</sup>    | 6 x 10 <sup>-4</sup>  | 1 x 10 <sup>-3</sup> | 2 x 10 <sup>-6</sup>  |      |
|                            | Cs 134               | S                | 3 x 10 <sup>-4</sup>    | 4 x 10 <sup>-8</sup>  | 9 x 10 <sup>-5</sup> | 1 x 10 <sup>-8</sup>  | 20   |
|                            |                      | I                | 1 x 10 <sup>-3</sup>    | 1 x 10 <sup>-8</sup>  | 4 x 10 <sup>-4</sup> | 4 x 10 <sup>-9</sup>  |      |
|                            | Cs 135               | S                | 3 x 10 <sup>-3</sup>    | 5 x 10 <sup>-7</sup>  | 1 x 10 <sup>-3</sup> | 2 x 10 <sup>-7</sup>  | 200  |
|                            |                      | I                | 7 x 10 <sup>-3</sup>    | 9 x 10 <sup>-8</sup>  | 2 x 10 <sup>-3</sup> | 3 x 10 <sup>-8</sup>  |      |
|                            | Cs 136               | S                | 2 x 10 <sup>-3</sup>    | 4 x 10 <sup>-7</sup>  | 9 x 10 <sup>-4</sup> | 1 x 10 <sup>-7</sup>  | 30   |
|                            |                      | I                | 2 x 10 <sup>-3</sup>    | 2 x 10 <sup>-7</sup>  | 6 x 10 <sup>-4</sup> | 6 x 10 <sup>-8</sup>  |      |
|                            | Cs 137               | S                | 4 x 10 <sup>-4</sup>    | 6 x 10 <sup>-8</sup>  | 2 x 10 <sup>-4</sup> | 2 x 10 <sup>-8</sup>  | 30   |
|                            |                      | I                | 1 x 10 <sup>-3</sup>    | 1 x 10 <sup>-8</sup>  | 4 x 10 <sup>-4</sup> | 5 x 10 <sup>-9</sup>  |      |

TABLE III

MPBB<sup>6</sup>  
(body burden)  
( $\mu\text{c}$ )TABLE II<sup>4,5</sup>Column 1  
WATER  
( $\mu\text{c/cc}$ )Column 2  
AIR  
( $\mu\text{c/cc}$ )TABLE I<sup>3</sup>Column 1  
WATER  
( $\mu\text{c/cc}$ )Column 2  
AIR  
( $\mu\text{c/cc}$ )

TABLE III

| ELEMENT<br>(atomic number) | ISOTOPE <sup>1</sup> | TABLE I <sup>3</sup>                      |                                         | TABLE II <sup>4,5</sup>                   |                                         | MPBB <sup>6</sup><br>(body burden)<br>( $\mu\text{c}$ ) |
|----------------------------|----------------------|-------------------------------------------|-----------------------------------------|-------------------------------------------|-----------------------------------------|---------------------------------------------------------|
|                            |                      | Column 1<br>WATER<br>( $\mu\text{c/cc}$ ) | Column 2<br>AIR<br>( $\mu\text{c/cc}$ ) | Column 1<br>WATER<br>( $\mu\text{c/cc}$ ) | Column 2<br>AIR<br>( $\mu\text{c/cc}$ ) |                                                         |
| Chlorine<br>(17)           | Cl 36 S              | $2 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | $8 \times 10^{-4}$                        | $1 \times 10^{-7}$                      | 80                                                      |
|                            | Cl 37 I              | $2 \times 10^{-3}$                        | $2 \times 10^{-8}$                      | $6 \times 10^{-4}$                        | $8 \times 10^{-9}$                      | 9                                                       |
|                            | Cl 38 S              | $1 \times 10^{-2}$                        | $3 \times 10^{-6}$                      | $4 \times 10^{-3}$                        | $9 \times 10^{-7}$                      |                                                         |
| Chromium<br>(24)           | Cr 51 S              | $5 \times 10^{-2}$                        | $1 \times 10^{-3}$                      | $2 \times 10^{-2}$                        | $4 \times 10^{-6}$                      | 800                                                     |
|                            | Cr 52 I              | $5 \times 10^{-2}$                        | $2 \times 10^{-6}$                      | $2 \times 10^{-2}$                        | $8 \times 10^{-7}$                      |                                                         |
| Cobalt<br>(27)             | Co 57 S              | $2 \times 10^{-2}$                        | $3 \times 10^{-6}$                      | $5 \times 10^{-3}$                        | $1 \times 10^{-6}$                      | 200                                                     |
|                            | Co 58m S             | $1 \times 10^{-2}$                        | $2 \times 10^{-7}$                      | $4 \times 10^{-3}$                        | $6 \times 10^{-8}$                      |                                                         |
|                            | Co 58 I              | $8 \times 10^{-2}$                        | $2 \times 10^{-3}$                      | $3 \times 10^{-2}$                        | $6 \times 10^{-6}$                      | 200                                                     |
| Copper<br>(29)             | Co 58 S              | $6 \times 10^{-2}$                        | $9 \times 10^{-4}$                      | $2 \times 10^{-2}$                        | $3 \times 10^{-6}$                      | 30                                                      |
|                            | Co 60 S              | $4 \times 10^{-3}$                        | $8 \times 10^{-7}$                      | $1 \times 10^{-3}$                        | $3 \times 10^{-7}$                      |                                                         |
|                            | Co 60 I              | $3 \times 10^{-3}$                        | $5 \times 10^{-8}$                      | $9 \times 10^{-4}$                        | $2 \times 10^{-8}$                      | 10                                                      |
| Curium<br>(96)             | Cu 64 S              | $1 \times 10^{-3}$                        | $3 \times 10^{-7}$                      | $5 \times 10^{-4}$                        | $1 \times 10^{-7}$                      |                                                         |
|                            | Cu 64 I              | $1 \times 10^{-2}$                        | $9 \times 10^{-9}$                      | $3 \times 10^{-4}$                        | $3 \times 10^{-9}$                      |                                                         |
|                            | Cm 242 S             | $1 \times 10^{-2}$                        | $2 \times 10^{-6}$                      | $3 \times 10^{-3}$                        | $7 \times 10^{-7}$                      | 10                                                      |
| Dysprosium<br>(66)         | Cm 243 S             | $6 \times 10^{-3}$                        | $1 \times 10^{-6}$                      | $2 \times 10^{-3}$                        | $4 \times 10^{-7}$                      |                                                         |
|                            | Cm 244 S             | $7 \times 10^{-4}$                        | $1 \times 10^{-10}$                     | $2 \times 10^{-4}$                        | $4 \times 10^{-11}$                     | 0.05                                                    |
|                            | Cm 245 S             | $7 \times 10^{-4}$                        | $2 \times 10^{-10}$                     | $3 \times 10^{-4}$                        | $6 \times 10^{-11}$                     |                                                         |
| Erbium<br>(68)             | Cm 246 S             | $1 \times 10^{-4}$                        | $6 \times 10^{-12}$                     | $5 \times 10^{-5}$                        | $2 \times 10^{-12}$                     | 0.09                                                    |
|                            | Dy 165 S             | $7 \times 10^{-4}$                        | $1 \times 10^{-10}$                     | $2 \times 10^{-4}$                        | $3 \times 10^{-11}$                     |                                                         |
|                            | Dy 166 S             | $7 \times 10^{-4}$                        | $2 \times 10^{-12}$                     | $3 \times 10^{-4}$                        | $3 \times 10^{-12}$                     | 0.1                                                     |
| Europium<br>(63)           | Er 169 S             | $7 \times 10^{-4}$                        | $9 \times 10^{-12}$                     | $7 \times 10^{-5}$                        | $3 \times 10^{-11}$                     |                                                         |
|                            | Er 171 S             | $8 \times 10^{-4}$                        | $1 \times 10^{-10}$                     | $3 \times 10^{-4}$                        | $2 \times 10^{-12}$                     | 0.04                                                    |
|                            | Eu 152 S             | $1 \times 10^{-4}$                        | $5 \times 10^{-12}$                     | $4 \times 10^{-4}$                        | $4 \times 10^{-11}$                     |                                                         |
| Flourine<br>(9)            | Eu 152 S             | $1 \times 10^{-4}$                        | $5 \times 10^{-12}$                     | $3 \times 10^{-4}$                        | $2 \times 10^{-12}$                     | 0.05                                                    |
|                            | Eu 154 S             | $8 \times 10^{-4}$                        | $1 \times 10^{-10}$                     | $3 \times 10^{-4}$                        | $4 \times 10^{-11}$                     |                                                         |
|                            | Eu 155 S             | $1 \times 10^{-2}$                        | $3 \times 10^{-6}$                      | $4 \times 10^{-3}$                        | $9 \times 10^{-7}$                      | 10                                                      |
| Dysprosium<br>(66)         | Dy 165 S             | $1 \times 10^{-2}$                        | $3 \times 10^{-6}$                      | $4 \times 10^{-3}$                        | $7 \times 10^{-7}$                      |                                                         |
|                            | Dy 166 S             | $1 \times 10^{-2}$                        | $2 \times 10^{-6}$                      | $4 \times 10^{-3}$                        | $7 \times 10^{-7}$                      | 5                                                       |
|                            | Dy 167 I             | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                      | $4 \times 10^{-4}$                        | $7 \times 10^{-8}$                      |                                                         |
| Erbium<br>(68)             | Er 169 S             | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                      | $9 \times 10^{-4}$                        | $2 \times 10^{-7}$                      | 30                                                      |
|                            | Er 171 S             | $3 \times 10^{-3}$                        | $6 \times 10^{-7}$                      | $9 \times 10^{-4}$                        | $1 \times 10^{-7}$                      |                                                         |
|                            | Er 172 I             | $3 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                      | 9                                                       |
| Europium<br>(63)           | Eu 152 S             | $3 \times 10^{-3}$                        | $6 \times 10^{-7}$                      | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                      |                                                         |
|                            | Eu 152 S             | $2 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | $6 \times 10^{-4}$                        | $1 \times 10^{-7}$                      | 8                                                       |
|                            | Eu 154 S             | $2 \times 10^{-3}$                        | $3 \times 10^{-7}$                      | $8 \times 10^{-4}$                        | $1 \times 10^{-7}$                      | 20                                                      |
| Flourine<br>(9)            | Eu 155 S             | $2 \times 10^{-3}$                        | $1 \times 10^{-8}$                      | $8 \times 10^{-4}$                        | $6 \times 10^{-9}$                      |                                                         |
|                            | Eu 156 S             | $6 \times 10^{-4}$                        | $2 \times 10^{-9}$                      | $2 \times 10^{-4}$                        | $1 \times 10^{-9}$                      | 5                                                       |
|                            | Eu 157 S             | $6 \times 10^{-4}$                        | $7 \times 10^{-9}$                      | $2 \times 10^{-4}$                        | $2 \times 10^{-9}$                      | 70                                                      |
| Dysprosium<br>(66)         | Dy 165 S             | $6 \times 10^{-3}$                        | $9 \times 10^{-8}$                      | $2 \times 10^{-3}$                        | $3 \times 10^{-8}$                      |                                                         |
|                            | Dy 166 S             | $6 \times 10^{-3}$                        | $7 \times 10^{-8}$                      | $8 \times 10^{-3}$                        | $2 \times 10^{-8}$                      |                                                         |
|                            | Dy 167 I             | $2 \times 10^{-2}$                        | $5 \times 10^{-6}$                      | $5 \times 10^{-3}$                        | $2 \times 10^{-6}$                      | 20                                                      |



| ELEMENT<br>(atomic number) |         |     | TABLE I <sup>3</sup>                      |                                         | TABLE II <sup>4,5</sup>                   |                                         | TABLE III<br>MPBB <sup>6</sup><br>(body burden)<br>( $\mu\text{c}$ ) |
|----------------------------|---------|-----|-------------------------------------------|-----------------------------------------|-------------------------------------------|-----------------------------------------|----------------------------------------------------------------------|
|                            |         |     | Column 1<br>WATER<br>( $\mu\text{c/cc}$ ) | Column 2<br>AIR<br>( $\mu\text{c/cc}$ ) | Column 1<br>WATER<br>( $\mu\text{c/cc}$ ) | Column 2<br>AIR<br>( $\mu\text{c/cc}$ ) |                                                                      |
| Gadolinium<br>(64)         | Gd 153  | S   | $6 \times 10^{-3}$                        | $2 \times 10^{-7}$                      | $2 \times 10^{-3}$                        | $8 \times 10^{-8}$                      | 90                                                                   |
|                            | Gd 159  | S   | $6 \times 10^{-3}$                        | $9 \times 10^{-8}$                      | $2 \times 10^{-3}$                        | $3 \times 10^{-8}$                      | 20                                                                   |
| Gallium<br>(31)            | Ga 72   | S   | $2 \times 10^{-3}$                        | $5 \times 10^{-7}$                      | $8 \times 10^{-4}$                        | $2 \times 10^{-7}$                      | 5                                                                    |
|                            | Ga 71   | S   | $2 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | $8 \times 10^{-4}$                        | $1 \times 10^{-7}$                      | 100                                                                  |
| Germanium<br>(32)          | Ge 71   | S   | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                      | $4 \times 10^{-4}$                        | $8 \times 10^{-8}$                      | 40                                                                   |
|                            | Ge 76   | S   | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                      | $4 \times 10^{-4}$                        | $6 \times 10^{-8}$                      | 20                                                                   |
| Gold<br>(79)               | Au 196  | S   | $5 \times 10^{-3}$                        | $1 \times 10^{-6}$                      | $2 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | 70                                                                   |
|                            | Au 198  | S   | $4 \times 10^{-3}$                        | $6 \times 10^{-7}$                      | $1 \times 10^{-3}$                        | $3 \times 10^{-7}$                      | 4                                                                    |
| Hafnium<br>(72)            | Hf 181  | S   | $2 \times 10^{-3}$                        | $4 \times 10^{-8}$                      | $7 \times 10^{-4}$                        | $1 \times 10^{-8}$                      | 5                                                                    |
|                            | Hf 180  | S   | $2 \times 10^{-3}$                        | $7 \times 10^{-8}$                      | $7 \times 10^{-4}$                        | $3 \times 10^{-8}$                      | 1000                                                                 |
| Holmium<br>(67)            | Ho 166  | S   | $9 \times 10^{-4}$                        | $2 \times 10^{-7}$                      | $3 \times 10^{-4}$                        | $7 \times 10^{-8}$                      | 30                                                                   |
|                            | Ho 167  | S   | $9 \times 10^{-4}$                        | $2 \times 10^{-7}$                      | $3 \times 10^{-4}$                        | $4 \times 10^{-8}$                      | 6                                                                    |
| Hydrogen<br>(1)            | H3      | S   | $1 \times 10^{-1}$                        | $2 \times 10^{-3}$                      | $3 \times 10^{-2}$                        | $5 \times 10^{-6}$                      | 30                                                                   |
|                            | H3      | Sub | ..                                        | $2 \times 10^{-3}$                      | -                                         | $4 \times 10^{-4}$                      | 30                                                                   |
| Indium<br>(49)             | In 113m | S   | $4 \times 10^{-2}$                        | $8 \times 10^{-6}$                      | $1 \times 10^{-2}$                        | $3 \times 10^{-6}$                      | 3                                                                    |
|                            | In 114m | S   | $4 \times 10^{-2}$                        | $7 \times 10^{-6}$                      | $1 \times 10^{-2}$                        | $2 \times 10^{-6}$                      | 0.7                                                                  |
| Iodine<br>(53)             | I 126   | S   | $5 \times 10^{-3}$                        | $3 \times 10^{-7}$                      | $2 \times 10^{-3}$                        | $3 \times 10^{-9}$                      | 0.3                                                                  |
|                            | I 129   | S   | $1 \times 10^{-3}$                        | $2 \times 10^{-9}$                      | $4 \times 10^{-4}$                        | $6 \times 10^{-10}$                     | 0.3                                                                  |
| Iridium<br>(77)            | Ir 190  | S   | $6 \times 10^{-3}$                        | $1 \times 10^{-6}$                      | $2 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | 40                                                                   |
|                            | Ir 192  | S   | $1 \times 10^{-3}$                        | $4 \times 10^{-7}$                      | $2 \times 10^{-3}$                        | $1 \times 10^{-7}$                      | 6                                                                    |
|                            | Ir 194  | S   | $1 \times 10^{-3}$                        | $3 \times 10^{-7}$                      | $4 \times 10^{-4}$                        | $9 \times 10^{-9}$                      | 7                                                                    |
|                            | Ir 196  | S   | $9 \times 10^{-4}$                        | $2 \times 10^{-7}$                      | $3 \times 10^{-4}$                        | $5 \times 10^{-8}$                      |                                                                      |

| TABLE I <sup>3</sup>         |                      |                               | TABLE II <sup>4,5</sup>     |                               | TABLE III <sup>6</sup>      |                                                         |      |
|------------------------------|----------------------|-------------------------------|-----------------------------|-------------------------------|-----------------------------|---------------------------------------------------------|------|
|                              |                      |                               | Column 1                    | Column 2                      | Column 1                    | Column 2                                                |      |
| ELEMENT<br>(atomic number)   | ISOTOPE <sup>1</sup> | WATER<br>( $\mu\text{c/cc}$ ) | AIR<br>( $\mu\text{c/cc}$ ) | WATER<br>( $\mu\text{c/cc}$ ) | AIR<br>( $\mu\text{c/cc}$ ) | MPBB <sup>6</sup><br>(body burden)<br>( $\mu\text{c}$ ) |      |
| Iron<br>(26)                 | Fe 55                | S                             | $2 \times 10^{-2}$          | $9 \times 10^{-7}$            | $8 \times 10^{-3}$          | $3 \times 10^{-7}$                                      | 1000 |
|                              |                      | I                             | $7 \times 10^{-2}$          | $1 \times 10^{-6}$            | $2 \times 10^{-2}$          | $3 \times 10^{-7}$                                      |      |
|                              | Fe 59                | S                             | $2 \times 10^{-3}$          | $1 \times 10^{-7}$            | $6 \times 10^{-4}$          | $5 \times 10^{-8}$                                      | 20   |
|                              |                      | I                             | $2 \times 10^{-3}$          | $5 \times 10^{-8}$            | $5 \times 10^{-4}$          | $2 \times 10^{-8}$                                      |      |
| Krypton <sup>2</sup><br>(36) | Kr 85m               | Sub                           | -                           | $6 \times 10^{-6}$            | -                           | $1 \times 10^{-6}$                                      | -    |
|                              | Kr 85                | Sub                           | -                           | $1 \times 10^{-5}$            | -                           | $3 \times 10^{-6}$                                      | -    |
|                              | Kr 87                | Sub                           | -                           | $1 \times 10^{-6}$            | -                           | $2 \times 10^{-7}$                                      | -    |
| Lanthanum<br>(57)            | La 140               | S                             | $7 \times 10^{-4}$          | $2 \times 10^{-7}$            | $2 \times 10^{-4}$          | $5 \times 10^{-8}$                                      | 9    |
|                              |                      | I                             | $7 \times 10^{-4}$          | $1 \times 10^{-7}$            | $2 \times 10^{-4}$          | $4 \times 10^{-8}$                                      |      |
| Lead<br>(82)                 | Pb 203               | S                             | $1 \times 10^{-2}$          | $3 \times 10^{-6}$            | $4 \times 10^{-3}$          | $9 \times 10^{-7}$                                      | 30   |
|                              |                      | I                             | $1 \times 10^{-2}$          | $2 \times 10^{-6}$            | $4 \times 10^{-3}$          | $6 \times 10^{-7}$                                      |      |
|                              | Pb 210               | S                             | $4 \times 10^{-6}$          | $1 \times 10^{-10}$           | $1 \times 10^{-6}$          | $4 \times 10^{-11}$                                     | 0.4  |
|                              |                      | I                             | $5 \times 10^{-3}$          | $2 \times 10^{-10}$           | $2 \times 10^{-3}$          | $8 \times 10^{-11}$                                     |      |
|                              | Pb 212               | S                             | $6 \times 10^{-4}$          | $2 \times 10^{-8}$            | $2 \times 10^{-4}$          | $6 \times 10^{-9}$                                      | 0.02 |
|                              | I                    | $5 \times 10^{-4}$            | $2 \times 10^{-8}$          | $2 \times 10^{-4}$            | $7 \times 10^{-9}$          |                                                         |      |
| Lutetium<br>(71)             | Lu 177               | S                             | $3 \times 10^{-3}$          | $6 \times 10^{-7}$            | $1 \times 10^{-3}$          | $2 \times 10^{-7}$                                      | 20   |
|                              |                      | I                             | $3 \times 10^{-3}$          | $5 \times 10^{-7}$            | $1 \times 10^{-3}$          | $2 \times 10^{-7}$                                      |      |
| Manganese<br>(25)            | Mn 52                | S                             | $1 \times 10^{-3}$          | $2 \times 10^{-7}$            | $3 \times 10^{-4}$          | $7 \times 10^{-8}$                                      | 5    |
|                              |                      | I                             | $9 \times 10^{-4}$          | $1 \times 10^{-7}$            | $3 \times 10^{-4}$          | $5 \times 10^{-8}$                                      |      |
|                              | Mn 54                | S                             | $4 \times 10^{-3}$          | $4 \times 10^{-7}$            | $1 \times 10^{-3}$          | $1 \times 10^{-7}$                                      | 20   |
|                              |                      | I                             | $3 \times 10^{-3}$          | $4 \times 10^{-8}$            | $1 \times 10^{-3}$          | $1 \times 10^{-8}$                                      |      |
|                              | Mn 56                | S                             | $4 \times 10^{-3}$          | $8 \times 10^{-7}$            | $1 \times 10^{-3}$          | $3 \times 10^{-7}$                                      | 2    |
|                              | I                    | $3 \times 10^{-3}$            | $5 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          |                                                         |      |
| Mercury<br>(80)              | Hg 197m              | S                             | $6 \times 10^{-3}$          | $7 \times 10^{-7}$            | $2 \times 10^{-3}$          | $3 \times 10^{-7}$                                      | 4    |
|                              |                      | I                             | $5 \times 10^{-3}$          | $8 \times 10^{-7}$            | $2 \times 10^{-3}$          | $3 \times 10^{-7}$                                      |      |
|                              | Hg 197               | S                             | $9 \times 10^{-3}$          | $1 \times 10^{-6}$            | $3 \times 10^{-3}$          | $4 \times 10^{-7}$                                      | 20   |
|                              | I                    | $1 \times 10^{-2}$            | $3 \times 10^{-6}$          | $5 \times 10^{-3}$            | $9 \times 10^{-7}$          |                                                         |      |
| Hg 203                       | S                    | $5 \times 10^{-4}$            | $7 \times 10^{-8}$          | $2 \times 10^{-4}$            | $2 \times 10^{-8}$          | 4                                                       |      |
|                              | I                    | $3 \times 10^{-3}$            | $1 \times 10^{-7}$          | $1 \times 10^{-3}$            | $4 \times 10^{-8}$          |                                                         |      |
| Molybdenum<br>(42)           | Mo 99                | S                             | $5 \times 10^{-3}$          | $7 \times 10^{-7}$            | $2 \times 10^{-3}$          | $3 \times 10^{-7}$                                      | 8    |
|                              |                      | I                             | $1 \times 10^{-3}$          | $2 \times 10^{-7}$            | $4 \times 10^{-4}$          | $7 \times 10^{-8}$                                      |      |

| ELEMENT<br>(atomic number) |         |   | TABLE I <sup>3</sup>   |                      | TABLE II <sup>4,5</sup> |                      | MPBB <sup>6</sup><br>(body burden)<br>( $\mu$ c) |
|----------------------------|---------|---|------------------------|----------------------|-------------------------|----------------------|--------------------------------------------------|
|                            |         |   | Column 1               |                      | Column 2                |                      |                                                  |
|                            |         |   | WATER<br>( $\mu$ c/cc) | AIR<br>( $\mu$ c/cc) | WATER<br>( $\mu$ c/cc)  | AIR<br>( $\mu$ c/cc) |                                                  |
| Neodymium<br>(60)          | Nd 144  | S | $2 \times 10^{-3}$     | $8 \times 10^{-11}$  | $7 \times 10^{-4}$      | $3 \times 10^{-11}$  | 0.1                                              |
|                            |         |   | $2 \times 10^{-3}$     | $3 \times 10^{-10}$  | $8 \times 10^{-4}$      | $1 \times 10^{-10}$  | 10                                               |
|                            |         |   | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $6 \times 10^{-4}$      | $1 \times 10^{-7}$   |                                                  |
|                            |         |   | $2 \times 10^{-3}$     | $2 \times 10^{-7}$   | $6 \times 10^{-4}$      | $8 \times 10^{-8}$   | 3                                                |
| Neodymium                  | Nd 149  | S | $8 \times 10^{-3}$     | $2 \times 10^{-6}$   | $3 \times 10^{-3}$      | $6 \times 10^{-7}$   |                                                  |
|                            |         |   | $8 \times 10^{-3}$     | $1 \times 10^{-6}$   | $3 \times 10^{-3}$      | $5 \times 10^{-7}$   |                                                  |
|                            |         |   | $9 \times 10^{-5}$     | $4 \times 10^{-12}$  | $3 \times 10^{-3}$      | $1 \times 10^{-12}$  | 0.06                                             |
|                            |         |   | $9 \times 10^{-4}$     | $1 \times 10^{-10}$  | $3 \times 10^{-4}$      | $4 \times 10^{-11}$  | 30                                               |
| Neptunium<br>(93)          | Np 239  | S | $4 \times 10^{-3}$     | $8 \times 10^{-7}$   | $1 \times 10^{-3}$      | $3 \times 10^{-7}$   |                                                  |
|                            |         |   | $4 \times 10^{-3}$     | $7 \times 10^{-7}$   | $1 \times 10^{-3}$      | $2 \times 10^{-7}$   |                                                  |
|                            |         |   | $6 \times 10^{-3}$     | $5 \times 10^{-7}$   | $2 \times 10^{-3}$      | $2 \times 10^{-7}$   | 1000                                             |
|                            |         |   | $6 \times 10^{-2}$     | $8 \times 10^{-7}$   | $2 \times 10^{-2}$      | $3 \times 10^{-7}$   | 200                                              |
| Nickel<br>(28)             | Ni 63   | S | $8 \times 10^{-4}$     | $6 \times 10^{-8}$   | $3 \times 10^{-4}$      | $2 \times 10^{-8}$   | 4                                                |
|                            |         |   | $2 \times 10^{-2}$     | $3 \times 10^{-7}$   | $7 \times 10^{-3}$      | $1 \times 10^{-7}$   |                                                  |
|                            |         |   | $4 \times 10^{-3}$     | $9 \times 10^{-7}$   | $1 \times 10^{-3}$      | $3 \times 10^{-7}$   |                                                  |
|                            |         |   | $3 \times 10^{-3}$     | $5 \times 10^{-7}$   | $1 \times 10^{-3}$      | $2 \times 10^{-7}$   | 200                                              |
| Niobium<br>(41)            | Nb 93m- | S | $1 \times 10^{-2}$     | $1 \times 10^{-7}$   | $4 \times 10^{-3}$      | $4 \times 10^{-8}$   | 40                                               |
|                            |         |   | $1 \times 10^{-2}$     | $2 \times 10^{-7}$   | $4 \times 10^{-3}$      | $5 \times 10^{-8}$   | 10                                               |
|                            |         |   | $3 \times 10^{-3}$     | $5 \times 10^{-7}$   | $1 \times 10^{-3}$      | $2 \times 10^{-7}$   |                                                  |
|                            |         |   | $3 \times 10^{-3}$     | $1 \times 10^{-7}$   | $1 \times 10^{-3}$      | $3 \times 10^{-8}$   | 8                                                |
| Niobium                    | Nb 97   | S | $3 \times 10^{-2}$     | $6 \times 10^{-6}$   | $9 \times 10^{-3}$      | $2 \times 10^{-6}$   | 100                                              |
|                            |         |   | $3 \times 10^{-2}$     | $5 \times 10^{-6}$   | $9 \times 10^{-3}$      | $2 \times 10^{-6}$   | 20                                               |
|                            |         |   | $2 \times 10^{-3}$     | $5 \times 10^{-7}$   | $7 \times 10^{-4}$      | $2 \times 10^{-7}$   | 10                                               |
|                            |         |   | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $5 \times 10^{-4}$      | $9 \times 10^{-8}$   | 20                                               |
| Osmium<br>(76)             | Os 185  | S | $2 \times 10^{-3}$     | $5 \times 10^{-7}$   | $7 \times 10^{-4}$      | $2 \times 10^{-7}$   | 40                                               |
|                            |         |   | $2 \times 10^{-3}$     | $5 \times 10^{-8}$   | $7 \times 10^{-4}$      | $2 \times 10^{-8}$   | 10                                               |
|                            |         |   | $7 \times 10^{-3}$     | $2 \times 10^{-5}$   | $3 \times 10^{-2}$      | $6 \times 10^{-6}$   | 20                                               |
|                            |         |   | $7 \times 10^{-2}$     | $9 \times 10^{-4}$   | $2 \times 10^{-2}$      | $3 \times 10^{-4}$   | 10                                               |
| Osmium                     | Os 191  | S | $5 \times 10^{-3}$     | $1 \times 10^{-6}$   | $2 \times 10^{-3}$      | $4 \times 10^{-7}$   | 10                                               |
|                            |         |   | $5 \times 10^{-3}$     | $1 \times 10^{-7}$   | $2 \times 10^{-3}$      | $1 \times 10^{-7}$   | 20                                               |
|                            |         |   | $5 \times 10^{-3}$     | $4 \times 10^{-7}$   | $2 \times 10^{-3}$      | $1 \times 10^{-7}$   | 7                                                |
|                            |         |   | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $6 \times 10^{-4}$      | $1 \times 10^{-7}$   | 6                                                |
| Osmium                     | Os 193  | S | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $5 \times 10^{-4}$      | $9 \times 10^{-8}$   | 20                                               |
|                            |         |   | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $5 \times 10^{-4}$      | $9 \times 10^{-8}$   | 7                                                |
|                            |         |   | $1 \times 10^{-2}$     | $1 \times 10^{-6}$   | $3 \times 10^{-3}$      | $5 \times 10^{-7}$   | 20                                               |
|                            |         |   | $8 \times 10^{-3}$     | $7 \times 10^{-7}$   | $3 \times 10^{-3}$      | $3 \times 10^{-7}$   | 7                                                |
| Palladium<br>(46)          | Pd 109  | S | $3 \times 10^{-3}$     | $6 \times 10^{-7}$   | $9 \times 10^{-4}$      | $2 \times 10^{-7}$   | 7                                                |
|                            |         |   | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $7 \times 10^{-4}$      | $1 \times 10^{-7}$   | 6                                                |
|                            |         |   | $5 \times 10^{-4}$     | $7 \times 10^{-8}$   | $2 \times 10^{-4}$      | $2 \times 10^{-8}$   | 20                                               |
|                            |         |   | $7 \times 10^{-4}$     | $8 \times 10^{-8}$   | $2 \times 10^{-4}$      | $3 \times 10^{-8}$   | 7                                                |
| Phosphorus<br>(15)         | P 32    | S | $5 \times 10^{-4}$     | $7 \times 10^{-8}$   | $2 \times 10^{-4}$      | $2 \times 10^{-8}$   | 20                                               |
|                            |         |   | $7 \times 10^{-4}$     | $8 \times 10^{-8}$   | $2 \times 10^{-4}$      | $3 \times 10^{-8}$   | 7                                                |
|                            |         |   | $5 \times 10^{-4}$     | $7 \times 10^{-8}$   | $2 \times 10^{-4}$      | $2 \times 10^{-8}$   | 20                                               |
|                            |         |   | $7 \times 10^{-4}$     | $8 \times 10^{-8}$   | $2 \times 10^{-4}$      | $3 \times 10^{-8}$   | 7                                                |

| ELEMENT<br>(atomic number) | ISOTOPE <sup>1</sup> | Column 1                      |                             | Column 2                      |                             | Column 3                      |                             | MPDB<br>(body burden)<br>( $\mu\text{c}$ ) |
|----------------------------|----------------------|-------------------------------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|-----------------------------|--------------------------------------------|
|                            |                      | WATER<br>( $\mu\text{c/cc}$ ) | AIR<br>( $\mu\text{c/cc}$ ) | WATER<br>( $\mu\text{c/cc}$ ) | AIR<br>( $\mu\text{c/cc}$ ) | WATER<br>( $\mu\text{c/cc}$ ) | AIR<br>( $\mu\text{c/cc}$ ) |                                            |
| Platinum<br>(78)           | Pt 191 S             | $4 \times 10^{-3}$            | $8 \times 10^{-7}$          | $1 \times 10^{-3}$            | $3 \times 10^{-7}$          | $1 \times 10^{-3}$            | $3 \times 10^{-7}$          | 10                                         |
|                            | Pt 193m S            | $3 \times 10^{-3}$            | $6 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | 100                                        |
|                            | Pt 193 I             | $3 \times 10^{-2}$            | $7 \times 10^{-6}$          | $1 \times 10^{-2}$            | $7 \times 10^{-6}$          | $1 \times 10^{-2}$            | $2 \times 10^{-6}$          | 70                                         |
|                            | Pt 193 S             | $3 \times 10^{-2}$            | $5 \times 10^{-6}$          | $9 \times 10^{-3}$            | $1 \times 10^{-6}$          | $9 \times 10^{-3}$            | $4 \times 10^{-7}$          | 5                                          |
|                            | Pt 197m S            | $5 \times 10^{-2}$            | $3 \times 10^{-7}$          | $2 \times 10^{-2}$            | $3 \times 10^{-7}$          | $2 \times 10^{-2}$            | $1 \times 10^{-7}$          | 10                                         |
|                            | Pt 197 S             | $3 \times 10^{-2}$            | $6 \times 10^{-6}$          | $9 \times 10^{-3}$            | $5 \times 10^{-6}$          | $9 \times 10^{-3}$            | $2 \times 10^{-6}$          | 0.04                                       |
| Plutonium<br>(94)          | Pu 238 S             | $1 \times 10^{-4}$            | $2 \times 10^{-12}$         | $5 \times 10^{-3}$            | $7 \times 10^{-13}$         | $5 \times 10^{-3}$            | $7 \times 10^{-13}$         | 0.04                                       |
|                            | Pu 239 S             | $8 \times 10^{-4}$            | $3 \times 10^{-11}$         | $3 \times 10^{-4}$            | $1 \times 10^{-11}$         | $3 \times 10^{-4}$            | $1 \times 10^{-11}$         | 0.04                                       |
|                            | Pu 240 S             | $1 \times 10^{-4}$            | $2 \times 10^{-12}$         | $3 \times 10^{-4}$            | $6 \times 10^{-13}$         | $3 \times 10^{-4}$            | $1 \times 10^{-11}$         | 0.04                                       |
|                            | Pu 241 S             | $8 \times 10^{-4}$            | $4 \times 10^{-11}$         | $5 \times 10^{-3}$            | $1 \times 10^{-11}$         | $5 \times 10^{-3}$            | $6 \times 10^{-13}$         | 0.9                                        |
|                            | Pu 242 S             | $7 \times 10^{-3}$            | $9 \times 10^{-11}$         | $3 \times 10^{-3}$            | $3 \times 10^{-11}$         | $3 \times 10^{-3}$            | $3 \times 10^{-11}$         | 0.05                                       |
|                            | Pu 242 I             | $4 \times 10^{-4}$            | $4 \times 10^{-12}$         | $5 \times 10^{-3}$            | $6 \times 10^{-13}$         | $5 \times 10^{-3}$            | $6 \times 10^{-13}$         | 0.03                                       |
| Polonium<br>(84)           | Po 210 S             | $2 \times 10^{-3}$            | $5 \times 10^{-10}$         | $7 \times 10^{-4}$            | $2 \times 10^{-10}$         | $7 \times 10^{-4}$            | $2 \times 10^{-10}$         | 10                                         |
|                            | Po 210 I             | $8 \times 10^{-4}$            | $2 \times 10^{-10}$         | $3 \times 10^{-4}$            | $7 \times 10^{-11}$         | $3 \times 10^{-4}$            | $7 \times 10^{-11}$         | 7                                          |
| Potassium<br>(19)          | K 42 S               | $9 \times 10^{-3}$            | $2 \times 10^{-6}$          | $3 \times 10^{-3}$            | $7 \times 10^{-7}$          | $3 \times 10^{-3}$            | $7 \times 10^{-7}$          | 20                                         |
|                            | K 42 I               | $6 \times 10^{-4}$            | $1 \times 10^{-7}$          | $2 \times 10^{-4}$            | $4 \times 10^{-8}$          | $2 \times 10^{-4}$            | $4 \times 10^{-8}$          | 60                                         |
| Praseodymium<br>(59)       | Pr 142 S             | $9 \times 10^{-4}$            | $2 \times 10^{-7}$          | $3 \times 10^{-4}$            | $7 \times 10^{-8}$          | $3 \times 10^{-4}$            | $7 \times 10^{-8}$          | 20                                         |
|                            | Pr 143 S             | $9 \times 10^{-4}$            | $2 \times 10^{-7}$          | $3 \times 10^{-4}$            | $7 \times 10^{-8}$          | $3 \times 10^{-4}$            | $7 \times 10^{-8}$          | 0.07                                       |
| Promethium<br>(61)         | Pm 147 S             | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | $5 \times 10^{-4}$            | $6 \times 10^{-8}$          | $2 \times 10^{-3}$            | $6 \times 10^{-8}$          | 0.02                                       |
|                            | Pm 149 S             | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | $5 \times 10^{-4}$            | $6 \times 10^{-8}$          | $2 \times 10^{-3}$            | $6 \times 10^{-8}$          | 40                                         |
| Protactinium<br>(91)       | Pa 230 S             | $7 \times 10^{-3}$            | $2 \times 10^{-9}$          | $2 \times 10^{-3}$            | $6 \times 10^{-10}$         | $2 \times 10^{-3}$            | $6 \times 10^{-10}$         | 0.05                                       |
|                            | Pa 231 S             | $7 \times 10^{-3}$            | $8 \times 10^{-10}$         | $2 \times 10^{-3}$            | $8 \times 10^{-10}$         | $2 \times 10^{-3}$            | $8 \times 10^{-10}$         | 0.06                                       |
| Radium<br>(88)             | Ra 223 S             | $3 \times 10^{-3}$            | $2 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | 0.1                                        |
|                            | Ra 224 S             | $2 \times 10^{-3}$            | $2 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | $1 \times 10^{-3}$            | $2 \times 10^{-7}$          | 0.06                                       |
| Radon<br>(86)              | Rn 220 S             | $2 \times 10^{-4}$            | $3 \times 10^{-7}$          | $7 \times 10^{-4}$            | $1 \times 10^{-7}$          | $7 \times 10^{-4}$            | $1 \times 10^{-7}$          | -                                          |
|                            | Rn 222 S             | $7 \times 10^{-4}$            | $4 \times 10^{-11}$         | $3 \times 10^{-4}$            | $1 \times 10^{-11}$         | $3 \times 10^{-4}$            | $1 \times 10^{-11}$         | -                                          |

| ELEMENT<br>(atomic number) | ISOTOPE <sup>1</sup> | TABLE I <sup>3</sup>   |                      | TABLE II <sup>4, 5</sup> |                      | TABLE III <sup>6</sup><br>MPBB <sub>6</sub><br>(body burden)<br>( $\mu$ c) |
|----------------------------|----------------------|------------------------|----------------------|--------------------------|----------------------|----------------------------------------------------------------------------|
|                            |                      | Column 1               | Column 2             | Column 1                 | Column 2             |                                                                            |
|                            |                      | WATER<br>( $\mu$ c/cc) | AIR<br>( $\mu$ c/cc) | WATER<br>( $\mu$ c/cc)   | AIR<br>( $\mu$ c/cc) |                                                                            |
| Rhenium<br>(75)            | Re 183               | $2 \times 10^{-2}$     | $3 \times 10^{-6}$   | $6 \times 10^{-3}$       | $9 \times 10^{-7}$   | 80                                                                         |
|                            | I                    | $8 \times 10^{-3}$     | $2 \times 10^{-7}$   | $3 \times 10^{-3}$       | $5 \times 10^{-8}$   |                                                                            |
|                            | Re 186               | $3 \times 10^{-3}$     | $6 \times 10^{-7}$   | $9 \times 10^{-4}$       | $2 \times 10^{-7}$   | 20                                                                         |
|                            | I                    | $1 \times 10^{-3}$     | $2 \times 10^{-7}$   | $5 \times 10^{-4}$       | $8 \times 10^{-8}$   |                                                                            |
|                            | Re 187               | $7 \times 10^{-2}$     | $9 \times 10^{-6}$   | $3 \times 10^{-2}$       | $3 \times 10^{-6}$   | 300                                                                        |
| Rhodium<br>(45)            | Re 188               | $4 \times 10^{-2}$     | $5 \times 10^{-7}$   | $2 \times 10^{-2}$       | $2 \times 10^{-7}$   | 7                                                                          |
|                            | I                    | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $6 \times 10^{-4}$       | $1 \times 10^{-7}$   |                                                                            |
|                            | I                    | $9 \times 10^{-4}$     | $2 \times 10^{-7}$   | $3 \times 10^{-4}$       | $6 \times 10^{-8}$   |                                                                            |
|                            | Rh 103m              | $4 \times 10^{-1}$     | $8 \times 10^{-3}$   | $1 \times 10^{-1}$       | $3 \times 10^{-3}$   | 200                                                                        |
|                            | I                    | $3 \times 10^{-1}$     | $6 \times 10^{-3}$   | $1 \times 10^{-1}$       | $2 \times 10^{-3}$   |                                                                            |
| Rubidium<br>(37)           | Rh 105               | $4 \times 10^{-3}$     | $8 \times 10^{-7}$   | $1 \times 10^{-3}$       | $3 \times 10^{-7}$   | 40                                                                         |
|                            | S                    | $3 \times 10^{-3}$     | $5 \times 10^{-7}$   | $1 \times 10^{-3}$       | $2 \times 10^{-7}$   |                                                                            |
|                            | I                    | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $7 \times 10^{-4}$       | $1 \times 10^{-7}$   | 30                                                                         |
|                            | Rb 86                | $7 \times 10^{-4}$     | $7 \times 10^{-8}$   | $2 \times 10^{-4}$       | $2 \times 10^{-8}$   |                                                                            |
|                            | I                    | $3 \times 10^{-3}$     | $5 \times 10^{-7}$   | $1 \times 10^{-3}$       | $2 \times 10^{-7}$   | 200                                                                        |
| Ruthenium<br>(44)          | Rb 87                | $5 \times 10^{-3}$     | $7 \times 10^{-8}$   | $2 \times 10^{-3}$       | $2 \times 10^{-8}$   |                                                                            |
|                            | I                    | $1 \times 10^{-2}$     | $2 \times 10^{-6}$   | $4 \times 10^{-3}$       | $8 \times 10^{-7}$   | 30                                                                         |
|                            | Ru 97                | $1 \times 10^{-2}$     | $2 \times 10^{-6}$   | $3 \times 10^{-3}$       | $6 \times 10^{-7}$   |                                                                            |
|                            | I                    | $2 \times 10^{-3}$     | $5 \times 10^{-7}$   | $8 \times 10^{-4}$       | $3 \times 10^{-8}$   | 20                                                                         |
|                            | Ru 103               | $2 \times 10^{-3}$     | $8 \times 10^{-8}$   | $1 \times 10^{-3}$       | $2 \times 10^{-7}$   | 2                                                                          |
| Samarium<br>(62)           | Ru 105               | $3 \times 10^{-3}$     | $7 \times 10^{-7}$   | $1 \times 10^{-3}$       | $2 \times 10^{-7}$   | 3                                                                          |
|                            | I                    | $3 \times 10^{-3}$     | $5 \times 10^{-7}$   | $1 \times 10^{-3}$       | $3 \times 10^{-8}$   |                                                                            |
|                            | Ru 106               | $4 \times 10^{-4}$     | $8 \times 10^{-8}$   | $1 \times 10^{-4}$       | $2 \times 10^{-9}$   | 0.1                                                                        |
|                            | I                    | $3 \times 10^{-4}$     | $6 \times 10^{-9}$   | $6 \times 10^{-4}$       | $9 \times 10^{-11}$  | 100                                                                        |
|                            | Sm 147               | $2 \times 10^{-3}$     | $7 \times 10^{-11}$  | $7 \times 10^{-4}$       | $2 \times 10^{-11}$  | 20                                                                         |
| Scandium<br>(21)           | Sm 151               | $2 \times 10^{-3}$     | $3 \times 10^{-10}$  | $4 \times 10^{-3}$       | $5 \times 10^{-8}$   | 20                                                                         |
|                            | S                    | $1 \times 10^{-2}$     | $6 \times 10^{-8}$   | $4 \times 10^{-3}$       | $1 \times 10^{-7}$   |                                                                            |
|                            | Sm 153               | $2 \times 10^{-3}$     | $1 \times 10^{-7}$   | $8 \times 10^{-4}$       | $2 \times 10^{-7}$   | 10                                                                         |
|                            | I                    | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $4 \times 10^{-4}$       | $8 \times 10^{-8}$   | 50                                                                         |
|                            | Sc 46                | $1 \times 10^{-3}$     | $2 \times 10^{-7}$   | $4 \times 10^{-4}$       | $8 \times 10^{-9}$   | 9                                                                          |
| Selenium<br>(34)           | Sc 47                | $1 \times 10^{-3}$     | $2 \times 10^{-8}$   | $4 \times 10^{-4}$       | $2 \times 10^{-7}$   |                                                                            |
|                            | I                    | $3 \times 10^{-3}$     | $6 \times 10^{-7}$   | $9 \times 10^{-4}$       | $6 \times 10^{-8}$   | 90                                                                         |
|                            | Sc 48                | $8 \times 10^{-4}$     | $5 \times 10^{-7}$   | $3 \times 10^{-4}$       | $4 \times 10^{-8}$   |                                                                            |
|                            | I                    | $8 \times 10^{-4}$     | $1 \times 10^{-7}$   | $3 \times 10^{-4}$       | $5 \times 10^{-8}$   |                                                                            |
|                            | Se 75                | $9 \times 10^{-3}$     | $1 \times 10^{-6}$   | $3 \times 10^{-3}$       | $4 \times 10^{-7}$   |                                                                            |
|                            | I                    | $8 \times 10^{-3}$     | $1 \times 10^{-7}$   | $3 \times 10^{-3}$       | $4 \times 10^{-8}$   |                                                                            |

| ELEMENT<br>(atomic number)            | ISOTOPE <sup>1</sup>                     | TABLE I <sup>3</sup>                     |                                           | TABLE II <sup>4, 5</sup>                 |                                           | TABLE III<br>MPBB <sup>6</sup><br>(body burden)<br>( $\mu$ c) |
|---------------------------------------|------------------------------------------|------------------------------------------|-------------------------------------------|------------------------------------------|-------------------------------------------|---------------------------------------------------------------|
|                                       |                                          | Column 1                                 | Column 2                                  | Column 1                                 | Column 2                                  |                                                               |
|                                       |                                          | WATER<br>( $\mu$ c/cc)                   | AIR<br>( $\mu$ c/cc)                      | WATER<br>( $\mu$ c/cc)                   | AIR<br>( $\mu$ c/cc)                      |                                                               |
| Silicon<br>(14)<br><br>Silver<br>(47) | Si 31 S I                                | $3 \times 10^{-2}$<br>$6 \times 10^{-3}$ | $6 \times 10^{-8}$<br>$1 \times 10^{-6}$  | $9 \times 10^{-3}$<br>$2 \times 10^{-3}$ | $2 \times 10^{-6}$<br>$3 \times 10^{-7}$  | 10                                                            |
|                                       | Ag 105 S I                               | $3 \times 10^{-3}$                       | $6 \times 10^{-7}$                        | $1 \times 10^{-3}$                       | $2 \times 10^{-7}$                        | 30                                                            |
|                                       | Ag 110m S I                              | $3 \times 10^{-3}$<br>$9 \times 10^{-4}$ | $8 \times 10^{-8}$<br>$2 \times 10^{-7}$  | $1 \times 10^{-3}$<br>$3 \times 10^{-4}$ | $3 \times 10^{-8}$<br>$7 \times 10^{-8}$  | 10                                                            |
|                                       |                                          | $9 \times 10^{-4}$<br>$1 \times 10^{-3}$ | $1 \times 10^{-8}$<br>$3 \times 10^{-7}$  | $3 \times 10^{-4}$<br>$4 \times 10^{-4}$ | $3 \times 10^{-9}$<br>$1 \times 10^{-7}$  | 20                                                            |
|                                       | Ag 111 S I                               | $1 \times 10^{-3}$                       | $2 \times 10^{-7}$                        | $4 \times 10^{-4}$                       | $8 \times 10^{-8}$                        |                                                               |
|                                       | Sodium<br>(11)                           | Na 22 S I                                | $1 \times 10^{-3}$                        | $2 \times 10^{-7}$                       | $4 \times 10^{-4}$                        | $6 \times 10^{-8}$                                            |
| Na 24 S I                             |                                          | $9 \times 10^{-4}$<br>$6 \times 10^{-3}$ | $9 \times 10^{-9}$<br>$1 \times 10^{-6}$  | $3 \times 10^{-4}$<br>$2 \times 10^{-4}$ | $3 \times 10^{-9}$<br>$4 \times 10^{-7}$  | 7                                                             |
|                                       |                                          | $8 \times 10^{-4}$                       | $1 \times 10^{-7}$                        | $3 \times 10^{-4}$                       | $5 \times 10^{-8}$                        |                                                               |
| Strontium<br>(38)                     | Sr 85m S I                               | $2 \times 10^{-1}$                       | $4 \times 10^{-3}$                        | $7 \times 10^{-2}$                       | $1 \times 10^{-3}$                        | 50                                                            |
|                                       | Sr 85 S I                                | $2 \times 10^{-1}$<br>$3 \times 10^{-3}$ | $3 \times 10^{-3}$<br>$2 \times 10^{-7}$  | $7 \times 10^{-2}$<br>$1 \times 10^{-3}$ | $1 \times 10^{-3}$<br>$8 \times 10^{-8}$  | 60                                                            |
|                                       |                                          | $5 \times 10^{-3}$                       | $1 \times 10^{-7}$                        | $2 \times 10^{-3}$                       | $4 \times 10^{-8}$                        |                                                               |
|                                       | Sr 89 S I                                | $3 \times 10^{-4}$                       | $3 \times 10^{-8}$                        | $1 \times 10^{-4}$                       | $1 \times 10^{-8}$                        | 4                                                             |
|                                       | Sr 90 S I                                | $8 \times 10^{-4}$<br>$4 \times 10^{-6}$ | $4 \times 10^{-8}$<br>$3 \times 10^{-10}$ | $3 \times 10^{-4}$<br>$1 \times 10^{-6}$ | $1 \times 10^{-8}$<br>$1 \times 10^{-10}$ | 2                                                             |
|                                       |                                          | $1 \times 10^{-3}$                       | $5 \times 10^{-9}$                        | $4 \times 10^{-4}$                       | $2 \times 10^{-9}$                        | 3                                                             |
|                                       | Sr 91 S I                                | $2 \times 10^{-3}$                       | $4 \times 10^{-7}$                        | $7 \times 10^{-4}$                       | $2 \times 10^{-7}$                        |                                                               |
|                                       | Sr 92 S I                                | $1 \times 10^{-3}$<br>$2 \times 10^{-3}$ | $3 \times 10^{-7}$<br>$4 \times 10^{-7}$  | $5 \times 10^{-4}$<br>$7 \times 10^{-4}$ | $9 \times 10^{-8}$<br>$2 \times 10^{-7}$  | 2                                                             |
|                                       |                                          | $2 \times 10^{-3}$                       | $3 \times 10^{-7}$                        | $6 \times 10^{-4}$                       | $1 \times 10^{-7}$                        |                                                               |
|                                       | Sulfur<br>(16)                           | S 35 S I                                 | $2 \times 10^{-3}$                        | $3 \times 10^{-7}$                       | $6 \times 10^{-4}$                        | $9 \times 10^{-8}$                                            |
| Tantalum<br>(73)                      | Ta 182 S I                               | $8 \times 10^{-3}$                       | $3 \times 10^{-7}$                        | $3 \times 10^{-3}$                       | $9 \times 10^{-8}$                        |                                                               |
|                                       |                                          | $1 \times 10^{-3}$                       | $4 \times 10^{-8}$                        | $4 \times 10^{-4}$                       | $1 \times 10^{-8}$                        | 7                                                             |
| Technetium<br>(43)                    | Tc 96m S I                               | $1 \times 10^{-3}$                       | $2 \times 10^{-8}$                        | $4 \times 10^{-4}$                       | $7 \times 10^{-9}$                        |                                                               |
|                                       |                                          | $4 \times 10^{-1}$                       | $8 \times 10^{-5}$                        | $1 \times 10^{-1}$                       | $3 \times 10^{-5}$                        | 60                                                            |
|                                       | Tc 96 S I                                | $3 \times 10^{-1}$                       | $3 \times 10^{-5}$                        | $1 \times 10^{-1}$                       | $1 \times 10^{-5}$                        |                                                               |
|                                       | Tc 97m S I                               | $3 \times 10^{-3}$<br>$1 \times 10^{-2}$ | $6 \times 10^{-7}$<br>$2 \times 10^{-6}$  | $1 \times 10^{-3}$<br>$4 \times 10^{-3}$ | $2 \times 10^{-7}$<br>$8 \times 10^{-7}$  | 10                                                            |
|                                       |                                          | $1 \times 10^{-2}$<br>$5 \times 10^{-3}$ | $2 \times 10^{-7}$<br>$2 \times 10^{-7}$  | $5 \times 10^{-4}$<br>$2 \times 10^{-3}$ | $8 \times 10^{-8}$<br>$5 \times 10^{-8}$  | 20                                                            |
|                                       | Tc 97 S I                                | $5 \times 10^{-2}$                       | $1 \times 10^{-5}$                        | $2 \times 10^{-2}$                       | $4 \times 10^{-6}$                        | 60                                                            |
|                                       | Tc 99m S I                               | $2 \times 10^{-2}$                       | $3 \times 10^{-7}$                        | $8 \times 10^{-3}$                       | $1 \times 10^{-7}$                        |                                                               |
|                                       | Tc 99 S I                                | $2 \times 10^{-1}$<br>$8 \times 10^{-2}$ | $4 \times 10^{-5}$<br>$1 \times 10^{-5}$  | $6 \times 10^{-2}$<br>$3 \times 10^{-3}$ | $1 \times 10^{-5}$<br>$5 \times 10^{-6}$  | 200                                                           |
|                                       | $1 \times 10^{-2}$<br>$5 \times 10^{-3}$ | $2 \times 10^{-6}$<br>$6 \times 10^{-8}$ | $3 \times 10^{-3}$<br>$2 \times 10^{-3}$  | $7 \times 10^{-7}$<br>$2 \times 10^{-8}$ | 10                                        |                                                               |

| ELEMENT<br>(atomic number) | ISOTOPE <sup>1</sup> | TABLE I <sup>2</sup>               |                                  | TABLE II <sup>4, 5</sup>           |                                  | TABLE III<br>MPBB %<br>(body burden)<br>( $\mu$ c) |
|----------------------------|----------------------|------------------------------------|----------------------------------|------------------------------------|----------------------------------|----------------------------------------------------|
|                            |                      | Column 1<br>WATER<br>( $\mu$ c/cc) | Column 2<br>AIR<br>( $\mu$ c/cc) | Column 1<br>WATER<br>( $\mu$ c/cc) | Column 2<br>AIR<br>( $\mu$ c/cc) |                                                    |
| Tellurium<br>(52)          | Te 125m              | S                                  | $4 \times 10^{-7}$               | $2 \times 10^{-3}$                 | $1 \times 10^{-7}$               | 20                                                 |
|                            | Te 127m              | I                                  | $3 \times 10^{-3}$               | $1 \times 10^{-7}$                 | $4 \times 10^{-8}$               | 7                                                  |
|                            | Te 127               | S                                  | $2 \times 10^{-3}$               | $1 \times 10^{-7}$                 | $5 \times 10^{-8}$               | 20                                                 |
|                            | Te 127               | I                                  | $2 \times 10^{-3}$               | $4 \times 10^{-8}$                 | $1 \times 10^{-8}$               | 3                                                  |
|                            | Te 129m              | S                                  | $8 \times 10^{-3}$               | $2 \times 10^{-7}$                 | $6 \times 10^{-7}$               | 5                                                  |
|                            | Te 129m              | I                                  | $5 \times 10^{-3}$               | $9 \times 10^{-7}$                 | $3 \times 10^{-7}$               | 4                                                  |
|                            | Te 129               | S                                  | $1 \times 10^{-3}$               | $8 \times 10^{-8}$                 | $3 \times 10^{-8}$               | 3                                                  |
|                            | Te 129               | I                                  | $6 \times 10^{-4}$               | $3 \times 10^{-8}$                 | $1 \times 10^{-8}$               | 5                                                  |
|                            | Te 131m              | S                                  | $2 \times 10^{-2}$               | $5 \times 10^{-6}$                 | $2 \times 10^{-6}$               | 4                                                  |
|                            | Te 132               | S                                  | $2 \times 10^{-3}$               | $4 \times 10^{-7}$                 | $1 \times 10^{-7}$               | 3                                                  |
| Terbium<br>(65)            | Tb 160               | S                                  | $1 \times 10^{-3}$               | $1 \times 10^{-7}$                 | $4 \times 10^{-8}$               | 20                                                 |
|                            | Tb 160               | I                                  | $1 \times 10^{-3}$               | $3 \times 10^{-8}$                 | $1 \times 10^{-8}$               | 40                                                 |
|                            | Tl 200               | S                                  | $1 \times 10^{-2}$               | $3 \times 10^{-6}$                 | $4 \times 10^{-3}$               | 40                                                 |
| Thallium<br>(81)           | Tl 201               | S                                  | $7 \times 10^{-3}$               | $1 \times 10^{-6}$                 | $2 \times 10^{-3}$               | 20                                                 |
|                            | Tl 202               | S                                  | $5 \times 10^{-3}$               | $9 \times 10^{-7}$                 | $2 \times 10^{-3}$               | 10                                                 |
|                            | Tl 202               | I                                  | $4 \times 10^{-3}$               | $8 \times 10^{-7}$                 | $1 \times 10^{-3}$               | 0.02                                               |
|                            | Tl 204               | S                                  | $2 \times 10^{-3}$               | $2 \times 10^{-7}$                 | $7 \times 10^{-4}$               | 0.02                                               |
|                            | Tl 204               | I                                  | $3 \times 10^{-3}$               | $6 \times 10^{-7}$                 | $1 \times 10^{-3}$               | 0.05                                               |
|                            | Tl 204               | I                                  | $2 \times 10^{-3}$               | $3 \times 10^{-8}$                 | $6 \times 10^{-4}$               | 30                                                 |
| Thorium<br>(90)            | Th 227               | S                                  | $5 \times 10^{-4}$               | $3 \times 10^{-10}$                | $2 \times 10^{-4}$               | 0.04                                               |
|                            | Th 228               | S                                  | $5 \times 10^{-4}$               | $2 \times 10^{-10}$                | $2 \times 10^{-4}$               | 0.01                                               |
|                            | Th 230               | S                                  | $4 \times 10^{-4}$               | $9 \times 10^{-12}$                | $7 \times 10^{-5}$               | 4                                                  |
|                            | Th 231               | S                                  | $9 \times 10^{-5}$               | $6 \times 10^{-12}$                | $1 \times 10^{-4}$               | 9                                                  |
|                            | Th 231               | I                                  | $7 \times 10^{-3}$               | $2 \times 10^{-11}$                | $3 \times 10^{-3}$               | 90                                                 |
|                            | Th 232               | S                                  | $5 \times 10^{-3}$               | $1 \times 10^{-11}$                | $2 \times 10^{-3}$               |                                                    |
|                            | Th natural           | S                                  | $1 \times 10^{-3}$               | $2 \times 10^{-12}$                | $4 \times 10^{-4}$               |                                                    |
|                            | Th 234               | S                                  | $3 \times 10^{-4}$               | $2 \times 10^{-12}$                | $1 \times 10^{-4}$               |                                                    |
|                            | Th 234               | I                                  | $5 \times 10^{-4}$               | $4 \times 10^{-8}$                 | $2 \times 10^{-4}$               |                                                    |
|                            | Th 234               | I                                  | $5 \times 10^{-4}$               | $3 \times 10^{-9}$                 | $2 \times 10^{-4}$               |                                                    |
| Thulium<br>(69)            | Tm 170               | S                                  | $1 \times 10^{-3}$               | $4 \times 10^{-8}$                 | $5 \times 10^{-4}$               |                                                    |
|                            | Tm 171               | S                                  | $1 \times 10^{-3}$               | $3 \times 10^{-8}$                 | $5 \times 10^{-4}$               |                                                    |
|                            | Tm 171               | I                                  | $1 \times 10^{-2}$               | $1 \times 10^{-7}$                 | $5 \times 10^{-3}$               |                                                    |

| ELEMENT<br>(atomic number)    | ISOTOPE <sup>1</sup> | TABLE I <sup>3</sup>   |                      | TABLE II <sup>4, 5</sup> |                      | TABLE III<br>MPBB <sup>6</sup><br>(body burden)<br>( $\mu$ c) |       |
|-------------------------------|----------------------|------------------------|----------------------|--------------------------|----------------------|---------------------------------------------------------------|-------|
|                               |                      | Column 1               | Column 2             | Column 1                 | Column 2             |                                                               |       |
|                               |                      | WATER<br>( $\mu$ c/cc) | AIR<br>( $\mu$ c/cc) | WATER<br>( $\mu$ c/cc)   | AIR<br>( $\mu$ c/cc) |                                                               |       |
| Tin<br>(50)                   | Sn 113               | S                      | $2 \times 10^{-3}$   | $4 \times 10^{-7}$       | $9 \times 10^{-4}$   | $1 \times 10^{-7}$                                            | 30    |
|                               |                      | I                      | $2 \times 10^{-3}$   | $5 \times 10^{-8}$       | $8 \times 10^{-4}$   | $2 \times 10^{-8}$                                            |       |
|                               | Sn 125               | S                      | $5 \times 10^{-4}$   | $1 \times 10^{-7}$       | $2 \times 10^{-4}$   | $4 \times 10^{-8}$                                            | 7     |
|                               |                      | I                      | $5 \times 10^{-4}$   | $8 \times 10^{-8}$       | $2 \times 10^{-4}$   | $3 \times 10^{-8}$                                            |       |
| Tungsten<br>(Wolfram)<br>(74) | W 181                | S                      | $1 \times 10^{-2}$   | $2 \times 10^{-6}$       | $4 \times 10^{-3}$   | $8 \times 10^{-7}$                                            | 70    |
|                               |                      | I                      | $1 \times 10^{-2}$   | $1 \times 10^{-7}$       | $3 \times 10^{-3}$   | $4 \times 10^{-8}$                                            |       |
|                               | W 185                | S                      | $4 \times 10^{-3}$   | $8 \times 10^{-7}$       | $1 \times 10^{-3}$   | $3 \times 10^{-7}$                                            | 30    |
|                               |                      | I                      | $3 \times 10^{-3}$   | $1 \times 10^{-7}$       | $1 \times 10^{-3}$   | $4 \times 10^{-8}$                                            |       |
|                               | W 187                | S                      | $2 \times 10^{-3}$   | $1 \times 10^{-7}$       | $7 \times 10^{-4}$   | $2 \times 10^{-7}$                                            | 30    |
|                               |                      | I                      | $2 \times 10^{-3}$   | $3 \times 10^{-7}$       | $6 \times 10^{-4}$   | $1 \times 10^{-7}$                                            |       |
| Uranium<br>(92)               | U 230                | S                      | $1 \times 10^{-4}$   | $3 \times 10^{-10}$      | $5 \times 10^{-5}$   | $1 \times 10^{-10}$                                           | 0.007 |
|                               |                      | I                      | $1 \times 10^{-4}$   | $1 \times 10^{-10}$      | $5 \times 10^{-5}$   | $4 \times 10^{-11}$                                           |       |
|                               | U 232                | S                      | $8 \times 10^{-4}$   | $1 \times 10^{-10}$      | $3 \times 10^{-4}$   | $3 \times 10^{-11}$                                           | 0.01  |
|                               |                      | I                      | $8 \times 10^{-4}$   | $3 \times 10^{-11}$      | $3 \times 10^{-4}$   | $9 \times 10^{-12}$                                           |       |
|                               | U 233                | S                      | $9 \times 10^{-4}$   | $5 \times 10^{-10}$      | $3 \times 10^{-4}$   | $2 \times 10^{-10}$                                           | 0.05  |
|                               |                      | I                      | $9 \times 10^{-4}$   | $1 \times 10^{-10}$      | $3 \times 10^{-4}$   | $4 \times 10^{-11}$                                           |       |
|                               | U 234                | S                      | $9 \times 10^{-4}$   | $6 \times 10^{-10}$      | $3 \times 10^{-4}$   | $2 \times 10^{-10}$                                           | 0.05  |
|                               |                      | I                      | $9 \times 10^{-4}$   | $1 \times 10^{-10}$      | $3 \times 10^{-4}$   | $4 \times 10^{-11}$                                           |       |
|                               | U 235                | S                      | $8 \times 10^{-4}$   | $5 \times 10^{-10}$      | $3 \times 10^{-4}$   | $2 \times 10^{-10}$                                           | 0.03  |
|                               |                      | I                      | $8 \times 10^{-4}$   | $1 \times 10^{-10}$      | $3 \times 10^{-4}$   | $4 \times 10^{-11}$                                           |       |
|                               | U 236                | S                      | $1 \times 10^{-3}$   | $6 \times 10^{-10}$      | $3 \times 10^{-4}$   | $2 \times 10^{-10}$                                           | 0.06  |
| Vanadium<br>(23)              | U 238                | S                      | $1 \times 10^{-3}$   | $7 \times 10^{-11}$      | $4 \times 10^{-4}$   | $3 \times 10^{-11}$                                           | 0.005 |
|                               |                      | I                      | $1 \times 10^{-3}$   | $1 \times 10^{-10}$      | $4 \times 10^{-4}$   | $5 \times 10^{-11}$                                           |       |
|                               | V 48                 | S                      | $9 \times 10^{-4}$   | $2 \times 10^{-7}$       | $3 \times 10^{-4}$   | $6 \times 10^{-8}$                                            | 8     |
|                               | I                    | $8 \times 10^{-4}$     | $6 \times 10^{-8}$   | $3 \times 10^{-4}$       | $2 \times 10^{-8}$   |                                                               |       |
| Xenon <sup>2</sup><br>(54)    | Xe 131m              | Sub                    | -                    | $2 \times 10^{-3}$       | -                    | $4 \times 10^{-6}$                                            | -     |
|                               | Xe 133               | Sub                    | -                    | $1 \times 10^{-3}$       | -                    | $3 \times 10^{-6}$                                            | -     |
|                               | Xe 135               | Sub                    | -                    | $4 \times 10^{-6}$       | -                    | $1 \times 10^{-6}$                                            | -     |
| Ytterbium<br>(70)             | Yb 175               | S                      | $3 \times 10^{-3}$   | $7 \times 10^{-7}$       | $1 \times 10^{-3}$   | $2 \times 10^{-7}$                                            | 30    |
|                               |                      | I                      | $3 \times 10^{-3}$   | $6 \times 10^{-7}$       | $1 \times 10^{-3}$   | $2 \times 10^{-7}$                                            |       |



| ELEMENT<br>(atomic number)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | ISOTOPE <sup>1</sup> | TABLE I <sup>3</sup>   |                      | TABLE II <sup>4, 5</sup> |                      | TABLE III <sup>6</sup><br>MPBB <sup>6</sup><br>(body burden)<br>( $\mu$ c) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|------------------------|----------------------|--------------------------|----------------------|----------------------------------------------------------------------------|
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | Column 1               | Column 2             | Column 1                 | Column 2             |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | WATER<br>( $\mu$ c/cc) | AIR<br>( $\mu$ c/cc) | WATER<br>( $\mu$ c/cc)   | AIR<br>( $\mu$ c/cc) |                                                                            |
| Yttrium<br>(39)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Y 90                 | $6 \times 10^{-4}$     | $1 \times 10^{-7}$   | $2 \times 10^{-4}$       | $4 \times 10^{-8}$   | 3                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $6 \times 10^{-4}$     | $1 \times 10^{-7}$   | $2 \times 10^{-4}$       | $3 \times 10^{-8}$   |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Y 91m                | $1 \times 10^{-1}$     | $2 \times 10^{-3}$   | $3 \times 10^{-2}$       | $8 \times 10^{-6}$   | 5                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $1 \times 10^{-1}$     | $2 \times 10^{-3}$   | $3 \times 10^{-2}$       | $6 \times 10^{-6}$   |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Y 91                 | $8 \times 10^{-4}$     | $4 \times 10^{-8}$   | $3 \times 10^{-4}$       | $1 \times 10^{-8}$   | 5                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $8 \times 10^{-4}$     | $3 \times 10^{-8}$   | $3 \times 10^{-4}$       | $1 \times 10^{-8}$   |                                                                            |
| Zinc<br>(30)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Y 92                 | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $6 \times 10^{-4}$       | $1 \times 10^{-7}$   | 2                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $6 \times 10^{-4}$       | $1 \times 10^{-7}$   |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Y 93                 | $8 \times 10^{-4}$     | $2 \times 10^{-7}$   | $3 \times 10^{-4}$       | $6 \times 10^{-8}$   | 2                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $8 \times 10^{-4}$     | $1 \times 10^{-7}$   | $3 \times 10^{-4}$       | $5 \times 10^{-8}$   |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Zn 65                | $3 \times 10^{-3}$     | $1 \times 10^{-7}$   | $1 \times 10^{-3}$       | $4 \times 10^{-8}$   | 60                                                                         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $5 \times 10^{-3}$     | $6 \times 10^{-8}$   | $2 \times 10^{-3}$       | $2 \times 10^{-8}$   |                                                                            |
| Zirconium<br>(40)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Zn 69m               | $2 \times 10^{-3}$     | $4 \times 10^{-7}$   | $7 \times 10^{-4}$       | $1 \times 10^{-7}$   | 0.7                                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $6 \times 10^{-4}$       | $1 \times 10^{-7}$   |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Zn 69                | $5 \times 10^{-2}$     | $7 \times 10^{-6}$   | $2 \times 10^{-2}$       | $2 \times 10^{-6}$   | 0.8                                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $5 \times 10^{-2}$     | $9 \times 10^{-6}$   | $2 \times 10^{-2}$       | $3 \times 10^{-6}$   |                                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Zr 93                | $2 \times 10^{-2}$     | $1 \times 10^{-7}$   | $8 \times 10^{-3}$       | $4 \times 10^{-8}$   | 100                                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | I                    | $2 \times 10^{-2}$     | $3 \times 10^{-7}$   | $8 \times 10^{-3}$       | $1 \times 10^{-7}$   |                                                                            |
| Unidentified Radionuclides or<br>Mixtures of Radionuclides:<br>If Sr 90, I 126, I 129, I 131, Pb 210,<br>Po 210, At 211, Ra 223, Ra 224, Ra 226,<br>Ac 227, Ra 228, Th 230, Pa 231,<br>Th 232, and Th-nat are not present*<br>If Sr 90, I 129, Pb 210, Po 210,<br>Ra 223, Ra 226, Ra 228, Pa 231,<br>and Th-nat are not present*<br>If Sr 90, I 129, Pb 210, Ra 226, and<br>Ra 228 are not present*<br>If Ra 226 and Ra 228 are not present*<br>If the activity is due to any unidenti-<br>fied radionuclide or mixture of<br>radionuclides not listed |                      | $2 \times 10^{-3}$     | $1 \times 10^{-7}$   | $3 \times 10^{-5}$       | -                    | -                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | $2 \times 10^{-3}$     | $3 \times 10^{-7}$   | $2 \times 10^{-5}$       | -                    | -                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | $2 \times 10^{-3}$     | $1 \times 10^{-7}$   | $7 \times 10^{-6}$       | -                    | -                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | $2 \times 10^{-3}$     | $3 \times 10^{-8}$   | $7 \times 10^{-6}$       | -                    | -                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | $5 \times 10^{-4}$     | $1 \times 10^{-7}$   | $1 \times 10^{-6}$       | -                    | -                                                                          |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                      | $5 \times 10^{-4}$     | $9 \times 10^{-8}$   | $2 \times 10^{-6}$       | -                    | -                                                                          |

| ELEMENT<br>(atomic number)                                                                                                            | ISOTOPE <sup>1</sup> | TABLE I <sup>2</sup>   |                      | TABLE II <sup>4, 5</sup> |                      | TABLE III<br>MPBB <sup>6</sup><br>(body burden)<br>( $\mu$ c) |
|---------------------------------------------------------------------------------------------------------------------------------------|----------------------|------------------------|----------------------|--------------------------|----------------------|---------------------------------------------------------------|
|                                                                                                                                       |                      | Column 1               | Column 2             | Column 1                 | Column 2             |                                                               |
|                                                                                                                                       |                      | WATER<br>( $\mu$ c/cc) | AIR<br>( $\mu$ c/cc) | WATER<br>( $\mu$ c/cc)   | AIR<br>( $\mu$ c/cc) |                                                               |
| If there are no alpha-emitters and if beta-emitters Sr 90, I 129, Pb 210, Ac 227, Ra 228, Pa 230, Pu 241, and Bk 249 are not present* |                      |                        |                      |                          |                      |                                                               |
|                                                                                                                                       |                      | -                      | $4 \times 10^{-9}$   | -                        | $1 \times 10^{-9}$   | -                                                             |
| If there are no alpha-emitters and if beta-emitters Pb 210, Ac 227, Ra 228, and Pu 241 are not present*                               |                      |                        |                      |                          |                      |                                                               |
|                                                                                                                                       |                      | -                      | $4 \times 10^{-10}$  | -                        | $1 \times 10^{-10}$  | -                                                             |
| If there are no alpha-emitters and if beta-emitter Ac 227 is not present*                                                             |                      |                        |                      |                          |                      |                                                               |
|                                                                                                                                       |                      | -                      | $4 \times 10^{-11}$  | -                        | $1 \times 10^{-11}$  | -                                                             |
| If Ac 227, Pa 231, Th 230, Th 232, Th-nat, Pu 238, Pu 239, Pu 240, Pu 242, and Cf 249 are not present*                                |                      |                        |                      |                          |                      |                                                               |
|                                                                                                                                       |                      | -                      | $4 \times 10^{-12}$  | -                        | $1 \times 10^{-12}$  | -                                                             |
| If Pa 231, Th-nat, Pu 239, Pu 240, Pu 242, and Cf 249 are not present*                                                                |                      |                        |                      |                          |                      |                                                               |
|                                                                                                                                       |                      | -                      | $3 \times 10^{-12}$  | -                        | $7 \times 10^{-13}$  | -                                                             |
| If the activity is due to any unidentified radionuclide or mixture of radionuclides not listed                                        |                      |                        |                      |                          |                      |                                                               |
|                                                                                                                                       |                      | -                      | $2 \times 10^{-12}$  | -                        | $4 \times 10^{-13}$  | -                                                             |

\* In this case "not present" implies the concentration of the radionuclide in water or air is small compared with the MPC value in Tables I or II.

NOTE: In the case of a radionuclide which decays to form radioactive daughters, the MPC calculations assume that only the parent radionuclide enters the body, but the estimated dose rate includes all the energy released by the daughter elements formed in the body. There are two exceptional cases,  $Rn^{220}$  and  $Rn^{222}$ , where a state of equilibrium typical of that attained in ordinary air is assumed. These cases are discussed in detail in the ICRP Internal Radiation report. In all other cases it is assumed that only the parent element enters the body.

Where mixtures of radioisotopes are present or the dose to an organ from radioisotopes concentrations plus external sources must be considered, the reader is referred to National Bureau of Standards Handbook No. 69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure."

## APPENDIX A, PART 2

### PHYSICAL, BIOLOGICAL, AND EFFECTIVE HALF-LIFE, BODY BURDEN, ORGAN OF REFERENCE AND TYPE OF DECAY FOR VARIOUS ISOTOPES

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay           | Half-life (days)  |                                      | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|-----------------------------------------|-------------------|--------------------------------------|-------------------------------------|------------------------------------|
|                            |         |                                         | Physical<br>$T_r$ | Biological Effective<br>$T_b$<br>$T$ |                                     |                                    |
| Actinium<br>(89)           | Ac 227  | $\alpha$ , $\beta^+$ , $\gamma$         | $8 \times 10^3$   | $7.3 \times 10^4$                    | $7.2 \times 10^3$                   | Bone                               |
|                            | Ac 228  | $\alpha$ , $\beta^+$ , $\gamma$ , $e^-$ | 0.26              | $7.3 \times 10^4$                    | 0.26                                | Bone                               |
| Americium<br>(95)          | Am 241  | $\alpha$ , $\gamma$                     | $1.7 \times 10^5$ | $7.3 \times 10^4$                    | $5.1 \times 10^4$                   | Bone                               |
|                            | Am 243  | $\alpha$ , $\beta^+$ , $\gamma$         | $2.9 \times 10^6$ | $7.3 \times 10^4$                    | $7.1 \times 10^4$                   | Bone                               |
| Antimony<br>(51)           | Sb 122  | $\beta^+$ , $\gamma$                    | 2.8               | 38                                   | 2.6                                 | Total Body                         |
|                            | Sb 124  | $\beta^+$ , $\gamma$                    | 60                | 38                                   | 23                                  | Total Body                         |
|                            | Sb 125  | $\beta^+$ , $\gamma$ , $e^-$            | 876               | 100                                  | 90                                  | Lung                               |
| Argon<br>(18)              | A 37    | K                                       | 34.1              | -                                    | -                                   | -                                  |
|                            | A 41    | $\beta^+$ , $\gamma$                    | 0.076             | -                                    | -                                   | -                                  |
| Arsenic<br>(33)            | As 73   | K, $\gamma$                             | 76                | 280                                  | 60                                  | Total Body                         |
|                            | As 74   | $\beta^+$ , $\beta^+$ , K, $\gamma$     | 17.5              | 280                                  | 16.5                                | Total Body                         |
|                            | As 76   | $\beta^+$ , $\gamma$                    | 1.1               | 280                                  | 1.1                                 | Total Body                         |
|                            | As 77   | $\beta^+$ , $\gamma$                    | 1.6               | 280                                  | 1.6                                 | Total Body                         |
| Astatine<br>(85)           | At 211  | $\alpha$ , K, $\gamma$                  | 0.3               | 36                                   | 0.3                                 | Thyroid                            |
| Barium<br>(56)             | Ba 131  | K, $\gamma$                             | 11.6              | 65                                   | 9.8                                 | Total Body                         |
|                            | Ba 140  | $\beta^+$ , $\gamma$                    | 12.8              | 65                                   | 10.7                                | Bone                               |

<sup>1</sup>  $\alpha$ , alpha;  $\beta^+$  negative beta particle;  $\gamma$ , gamma;  $\beta^+$ , positive beta particle;  
 $e^-$ , internal conversion electron; K, electron capture.

<sup>2</sup> See Page 250.

| Element<br>(atomic number) | Isotope                    | Type of <sup>1</sup><br>Decay   | Half-life (days)  |                     | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|----------------------------|---------------------------------|-------------------|---------------------|-------------------------------------|------------------------------------|
|                            |                            |                                 | Physical<br>$T_r$ | Biological<br>$T_b$ |                                     |                                    |
| Berkelium<br>(97)          | Bk 249                     | $\alpha$ , $\beta^-$ , $\gamma$ | 290               | 7.3                 | 289                                 | Bone                               |
| Beryllium<br>(4)           | Be 7                       | K, $\gamma$                     | 53.6              | 180                 | 41                                  | Total Body                         |
| Bismuth<br>(83)            | Bi 206                     | K, $\gamma$                     | 6.4               | 6                   | 3.1                                 | Kidney                             |
|                            | Bi 207                     | K, $\gamma$                     | $2.9 \times 10^3$ | 6                   | 6                                   | Kidney                             |
|                            | Bi 210                     | $\alpha$ , $\beta^-$            | 5.0               | 6                   | 3                                   | Kidney                             |
|                            | Bi 212                     | $\alpha$ , $\beta^-$ , $\gamma$ | 0.042             | 6                   | 0.042                               | Kidney                             |
| Bromine<br>(35)            | Br 82                      | $\beta^-$ , $\gamma$            | 1.5               | 8                   | 1.3                                 | Total Body                         |
| Cadmium<br>(48)            | Cd 109                     | K, $\gamma$ , $e^-$             | 475               | 200                 | 140                                 | Liver                              |
|                            | Cd 115m                    | $\beta^-$ , $\gamma$ , $e^-$    | 43                | 200                 | 35                                  | Liver                              |
|                            | Cd 115                     | $\beta^-$ , $\gamma$ , $e^-$    | 2.2               | 200                 | 2.2                                 | Liver                              |
| Calcium<br>(20)            | Ca 45                      | $\beta^-$                       | 164               | $1.8 \times 10^4$   | 162                                 | Bone                               |
|                            | Ca 47                      | $\beta^-$ , $\gamma$            | 4.9               | $1.8 \times 10^4$   | 4.9                                 | Bone                               |
| Californium<br>(98)        | Cf 249                     | $\alpha$ , $\gamma$             | $1.7 \times 10^5$ | $7.3 \times 10^4$   | $5.1 \times 10^4$                   | Bone                               |
|                            | Cf 250                     | $\alpha$                        | $3.7 \times 10^3$ | $7.3 \times 10^4$   | $3.5 \times 10^3$                   | Bone                               |
|                            | Cf 252                     | $\alpha$ , $\gamma$             | 803               | $7.3 \times 10^4$   | 794                                 | Bone                               |
| Carbon<br>(6)              | C 14<br>(CO <sub>2</sub> ) | $\beta^-$                       | $2 \times 10^4$   | 12                  | 12                                  | Fat                                |
|                            | Ce 141                     | $\beta^-$ , $\gamma$            | 32                | 293                 | 29                                  | Liver                              |
| Cerium<br>(58)             | Ce 143                     | $\beta^-$ , $\gamma$            | 1.33              | 293                 | 1.32                                | Liver                              |
|                            | Ce 144                     | $\alpha$ , $\beta^-$ , $\gamma$ | 290               | $1.5 \times 10^3$   | 243                                 | Bone                               |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay   | Half-life (days)  |                     |                   | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|---------------------------------|-------------------|---------------------|-------------------|-------------------------------------|------------------------------------|
|                            |         |                                 | Physical<br>$T_r$ | Biological<br>$T_b$ | Effective<br>$T$  |                                     |                                    |
| Cesium<br>(55)             | Cs 131  | K                               | 10                | 70                  | 8.75              | 700                                 | Total Body                         |
|                            | Cs 134m | $\beta^-$ , $\gamma$ , $e^-$    | 0.13              | 70                  | 0.13              | 100                                 | Total Body                         |
|                            | Cs 134  | $\beta^-$ , $\gamma$            | 840               | 70                  | 65                | 20                                  | Total Body                         |
|                            | Cs 135  | $\beta^-$                       | $1.1 \times 10^9$ | 90                  | 90                | 200                                 | Liver                              |
|                            | Cs 136  | $\beta^-$ , $\gamma$            | 13                | 70                  | 11                | 30                                  | Total Body                         |
| Chlorine<br>(17)           | Cs 137  | $\beta^-$ , $\gamma$ , $e^-$    | $1.1 \times 10^4$ | 70                  | 70                | 30                                  | Total Body                         |
|                            | Cl 36   | $\beta^-$                       | $1.2 \times 10^8$ | 29                  | 29                | 80                                  | Total Body                         |
|                            | Cl 38   | $\beta^-$ , $\gamma$            | 0.026             | 29                  | 0.026             | 9                                   | Total Body                         |
|                            | Cr 51   | K, $\gamma$                     | 27.8              | 616                 | 26.6              | 800                                 | Total Body                         |
| Cobalt<br>(27)             | Co 57   | K, $\gamma$ , $e^-$             | 270               | 9.5                 | 9.2               | 200                                 | Total Body                         |
|                            | Co 58m  | $\beta^+$ , K, $\gamma$         | 0.38              | 9.5                 | 0.37              | 200                                 | Total Body                         |
|                            | Co 58   | $\beta^+$ , K                   | 72                | 9.5                 | 8.4               | 30                                  | Total Body                         |
|                            | Co 60   | $\beta^-$ , $\gamma$            | $1.9 \times 10^3$ | 9.5                 | 9.5               | 10                                  | Total Body                         |
| Copper<br>(29)             | Cu 64   | $\beta^-$ , $\beta^+$ , K       | 0.53              | 2                   | 0.42              | 10                                  | Spleen                             |
| Curium<br>(96)             | Cm 242  | $\alpha$ , $\gamma$             | 162.5             | $3 \times 10^3$     | 154.3             | 0.05                                | Liver                              |
|                            | Cm 243  | $\alpha$ , $\gamma$             | $1.3 \times 10^4$ | $7.3 \times 10^4$   | $1.1 \times 10^4$ | 0.09                                | Bone                               |
|                            | Cm 244  | $\alpha$ , $\gamma$             | $6.7 \times 10^3$ | $7.3 \times 10^4$   | $6.1 \times 10^3$ | 0.1                                 | Bone                               |
|                            | Cm 245  | $\alpha$ , $\beta^-$ , $\gamma$ | $7.3 \times 10^6$ | $7.3 \times 10^4$   | $7.2 \times 10^4$ | 0.04                                | Bone                               |
|                            | Cm 246  | $\alpha$                        | $2.4 \times 10^6$ | $7.3 \times 10^4$   | $7.1 \times 10^4$ | 0.05                                | Bone                               |

| Element<br>(atomic number) | Isotope                        | Type of <sup>1</sup><br>Decay | Half-life (days)  |                     |                    | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|--------------------------------|-------------------------------|-------------------|---------------------|--------------------|-------------------------------------|------------------------------------|
|                            |                                |                               | Physical<br>$T_r$ | Biological<br>$T_b$ | Effective<br>$T$   |                                     |                                    |
| Dysprosium<br>(66)         | Dy 165                         | $\beta^-$ , $\gamma$          | 0.097             | $1 \times 10^3$     | 0.097              | 10                                  | Bone                               |
|                            | Dy 166                         | $\beta^-$ , $\gamma$ , $e^-$  | 3.4               | $1 \times 10^3$     | 3.4                | 5                                   | Bone                               |
| Erbium<br>(68)             | Er 169                         | $\beta^-$ , $\gamma$          | 9.4               | $1 \times 10^3$     | 9.3                | 30                                  | Bone                               |
|                            | Er 171                         | $\beta^-$ , $\gamma$ , $e^-$  | 0.31              | $1 \times 10^3$     | 0.31               | 9                                   | Bone                               |
| Europium<br>(63)           | Eu 152<br>( $T_{1/2}=9.2$ hrs) | $\beta^-$ , K, $\gamma$       | 0.38              | 127                 | 0.38               | 8                                   | Liver                              |
|                            | Eu 152<br>( $T_{1/2}=13$ yrs.) | $\beta^-$ , K, $\gamma$       | $4.7 \times 10^3$ | $1.48 \times 10^3$  | $1.13 \times 10^3$ | 20                                  | Kidney                             |
|                            | Eu 154                         | $\beta^-$ , K, $\gamma$       | $5.8 \times 10^3$ | $1.48 \times 10^3$  | $1.18 \times 10^3$ | 5                                   | Kidney                             |
|                            | Eu 155                         | $\beta^-$ , $\gamma$          | 621               | $1.48 \times 10^3$  | 438                | 70                                  | Kidney                             |
| Fluorine<br>(9)            | F 18                           | $\beta^+$                     | 0.078             | $1.45 \times 10^3$  | 0.078              | 20                                  | Bone and<br>Teeth                  |
| Gadolinium<br>(64)         | Gd 153                         | K, $\gamma$ , $e^-$           | 236               | $1 \times 10^3$     | 191                | 90                                  | Bone                               |
|                            | Gd 159                         | $\beta^-$ , $\gamma$          | 0.75              | $1 \times 10^3$     | 0.75               | 20                                  | Bone                               |
| Gallium<br>(31)            | Ga 72                          | $\beta^-$ , $\gamma$          | 0.59              | 4.8                 | 0.53               | 5                                   | Liver                              |
| Germanium<br>(32)          | Ge 71                          | K                             | 12                | 12                  | 6                  | 100                                 | Kidney                             |
| Gold<br>(79)               | Au 196                         | $\beta^-$ , $\gamma$ , $e^-$  | 5.6               | 120                 | 5.4                | 40                                  | Total Body                         |
|                            | Au 198                         | $\beta^-$ , $\gamma$          | 2.7               | 280                 | 2.7                | 20                                  | Kidney                             |
|                            | Au 199                         | $\beta^-$ , $\gamma$          | 3.15              | 280                 | 3.1                | 70                                  | Kidney                             |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay   | Half-life (days)     |                     | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|---------------------------------|----------------------|---------------------|-------------------------------------|------------------------------------|
|                            |         |                                 | Physical<br>$T_r$    | Biological<br>$T_b$ |                                     |                                    |
| Hafnium<br>(72)            | Hf 181  | $\beta^-$ , $\gamma$            | 46                   | 350                 | 41                                  | Spleen                             |
| Holmium<br>(67)            | Ho 166  | $\beta^-$ , $\gamma$ , $e^-$    | 1.1                  | $1 \times 10^3$     | 1.1                                 | Bone                               |
| Hydrogen<br>(1)            | H 3     | $\beta^-$                       | $4.5 \times 10^3$    | 12                  | 12                                  | Body Tissue                        |
| Indium<br>(49)             | In 113m | $\gamma$ , $e^-$                | 0.073                | 60                  | 0.073                               | Kidney                             |
|                            | In 114m | $\beta^-$ , K, $\gamma$ , $e^-$ | 49                   | 60                  | 27                                  | Kidney                             |
|                            | In 115m | $\beta^-$ , $\gamma$ , $e^-$    | 0.19                 | 60                  | 0.19                                | Kidney                             |
|                            | In 115  | $\beta^-$                       | $2.2 \times 10^{17}$ | 60                  | 60                                  | Kidney                             |
| Iodine<br>(53)             | I 126   | $\beta^-$ , K, $\gamma$         | 13.3                 | 138                 | 12.1                                | Thyroid                            |
|                            | I 129   | $\beta^-$ , $\gamma$ , $e^-$    | $6.3 \times 10^9$    | 138                 | 138                                 | Thyroid                            |
|                            | I 131   | $\beta^-$ , $\gamma$ , $e^-$    | 8                    | 138                 | 7.6                                 | Thyroid                            |
|                            | I 132   | $\beta^-$ , $\gamma$ , $e^-$    | 0.097                | 138                 | 0.097                               | Thyroid                            |
|                            | I 133   | $\beta^-$ , $\gamma$ , $e^-$    | 0.87                 | 138                 | 0.87                                | Thyroid                            |
| Iridium<br>(77)            | I 134   | $\beta^-$ , $\gamma$            | 0.036                | 138                 | 0.036                               | Thyroid                            |
|                            | I 135   | $\beta^-$ , $\gamma$ , $e^-$    | 0.28                 | 138                 | 0.28                                | Thyroid                            |
|                            | Ir 190  | K, $\gamma$                     | 12                   | 27                  | 8.3                                 | Liver                              |
|                            | Ir 192  | $\beta^-$ , $\gamma$            | 74.5                 | 50                  | 30                                  | Kidney                             |
| Iron<br>(26)               | Ir 194  | $\beta^-$                       | 0.79                 | 50                  | 0.78                                | Kidney                             |
|                            | Fe 55   | K                               | $1.1 \times 10^3$    | 600                 | 388                                 | Spleen                             |
|                            | Fe 59   | $\beta^-$ , $\gamma$            | 45.1                 | 600                 | 41.9                                | Spleen                             |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay           | Half-life (days)  |                     |                  | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|-----------------------------------------|-------------------|---------------------|------------------|-------------------------------------|------------------------------------|
|                            |         |                                         | Physical<br>$T_r$ | Biological<br>$T_b$ | Effective<br>$T$ |                                     |                                    |
| Krypton<br>(36)            | Kr 85m  | $\beta^-$ , $\gamma$                    | 0.18              | -                   | -                | -                                   | Total Body                         |
|                            | Kr 85   | $\beta^-$                               | $3.9 \times 10^3$ | -                   | -                | -                                   | Total Body                         |
|                            | Kr 87   | $\beta^-$ , $\gamma$                    | 0.054             | -                   | -                | -                                   | Total Body                         |
| Lanthanum<br>(57)          | La 140  | $\beta^-$ , $\gamma$                    | 1.68              | 400                 | 1.68             | 9                                   | Liver                              |
| Lead<br>(82)               | Pb 203  | K, $\gamma$                             | 2.17              | 531                 | 2.16             | 30                                  | Kidney                             |
|                            | Pb 210  | $\alpha$ , $\beta^-$ , $\gamma$         | $7.1 \times 10^3$ | 531                 | 494              | 0.4                                 | Kidney                             |
|                            | Pb 212  | $\alpha$ , $\beta^-$ , $\gamma$ , $e^-$ | 0.44              | 531                 | 0.44             | 0.02                                | Kidney                             |
| Lutetium<br>(71)           | Lu 177  | $\beta^-$ , $\gamma$                    | 6.8               | $1 \times 10^3$     | 6.75             | 20                                  | Bone                               |
| Manganese<br>(25)          | Mn 52   | $\beta^+$ , K, $\gamma$                 | 5.55              | 5.7                 | 2.8              | 5                                   | Pancreas                           |
|                            | Mn 54   | K, $\gamma$                             | 300               | 25                  | 23               | 20                                  | Liver                              |
|                            | Mn 56   | $\beta^-$ , $\gamma$                    | 0.11              | 5.7                 | 0.11             | 2                                   | Pancreas                           |
| Mercury<br>(80)            | Hg 197m | K, $\gamma$ , $e^-$                     | 1                 | 14.5                | 0.94             | 4                                   | Kidney                             |
|                            | Hg 197  | K, $\gamma$ , $e^-$                     | 2.7               | 14.5                | 2.3              | 20                                  | Kidney                             |
|                            | Hg 203  | $\beta^-$ , $\gamma$ , $e^-$            | 45.8              | 14.5                | 11.0             | 4                                   | Kidney                             |
| Molybdenum<br>(42)         | Mo 99   | $\beta^-$ , $\gamma$                    | 2.79              | 3                   | 1.5              | 8                                   | Kidney                             |



| Element<br>(atomic number)     | Isotope | Type of <sup>1</sup><br>Decay | Half-life (days)     |                     |                   | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|--------------------------------|---------|-------------------------------|----------------------|---------------------|-------------------|-------------------------------------|------------------------------------|
|                                |         |                               | Physical<br>$T_r$    | Biological<br>$T_b$ | Effective<br>$T$  |                                     |                                    |
| Neodymium<br>(60)              | Nd 144  | $\alpha$                      | $7.3 \times 10^{17}$ | $1.5 \times 10^3$   | $1.5 \times 10^3$ | 0.1                                 | Bone                               |
|                                | Nd 147  | $\alpha, \beta^-, \gamma$     | 11.3                 | 131                 | 10                | 10                                  | Liver                              |
|                                | Nd 149  | $\beta^-, \gamma$             | 0.083                | 131                 | 0.083             | 3                                   | Liver                              |
| Neptunium<br>(93)              | Np 237  | $\alpha, \beta^-, \gamma$     | $8 \times 10^8$      | $7.3 \times 10^4$   | $7.3 \times 10^4$ | 0.06                                | Bone                               |
|                                | Np 239  | $\alpha, \beta^-, \gamma$     | 2.33                 | $7.3 \times 10^4$   | 2.33              | 30                                  | Bone                               |
| Nickel<br>(28)                 | Ni 59   | K                             | $2.9 \times 10^7$    | 800                 | 800               | 1000                                | Bone                               |
|                                | Ni 63   | $\beta^-$                     | $2.9 \times 10^4$    | 800                 | 492               | 200                                 | Bone                               |
|                                | Ni 65   | $\beta^-, \gamma$             | 0.11                 | 800                 | 0.11              | 4                                   | Bone                               |
|                                | Nb 93m  | $\gamma, e^-$                 | $3.7 \times 10^3$    | $1 \times 10^3$     | 787               | 200                                 | Bone                               |
| Niobium<br>(Columbium)<br>(41) | Nb 95   | $\beta^-, \gamma$             | 35                   | 760                 | 33.5              | 40                                  | Total Body                         |
|                                | Nb 97   | $\beta^-, \gamma$             | 0.051                | $1 \times 10^3$     | 0.051             | 10                                  | Bone                               |
| Osmium<br>(76)                 | Os 185  | K, $\gamma, e^-$              | 95                   | 5                   | 4.8               | 8                                   | Kidney                             |
|                                | Os 191m | $\beta^-, \gamma, e^-$        | 0.58                 | 5                   | 0.52              | 100                                 | Kidney                             |
|                                | Os 191  | $\beta^-, \gamma, e^-$        | 16                   | 5                   | 3.8               | 20                                  | Kidney                             |
|                                | Os 193  | $\beta^-$                     | 1.3                  | 5                   | 1                 | 10                                  | Kidney                             |
| Palladium<br>(46)              | Pd 103  | K, $\gamma, e^-$              | 17                   | 30                  | 11                | 20                                  | Kidney                             |
|                                | Pd 109  | $\beta^-, \gamma, e^-$        | 0.57                 | 30                  | 0.56              | 7                                   | Kidney                             |
| Phosphorus<br>(15)             | P 32    | $\beta^-$                     | 14.3                 | $1.16 \times 10^3$  | 14.1              | 6                                   | Bone                               |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay      | Half-life (days)      |                     | MPBB<br>(body burden)<br>( $\mu\text{c}$ ) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|------------------------------------|-----------------------|---------------------|--------------------------------------------|------------------------------------|
|                            |         |                                    | Physical<br>$T_{1/2}$ | Biological<br>$T_b$ |                                            |                                    |
| Platinum<br>(78)           | Pt 191  | K, $\gamma$                        | 3                     | 60                  | 2.9                                        | Kidney                             |
|                            | Pt 193m | K, $\gamma$                        | 3.4                   | 60                  | 3.2                                        | Kidney                             |
|                            | Pt 193  | K                                  | $1.8 \times 10^5$     | 60                  | 60                                         | Kidney                             |
|                            | Pt 197m | $\beta^-$ , $\gamma$ , $e^-$       | 0.056                 | 60                  | 0.056                                      | Kidney                             |
|                            | Pt 197  | $\beta^-$ , $\gamma$               | 0.75                  | 60                  | 0.74                                       | Kidney                             |
| Plutonium<br>(94)          | Pu 238  | $\alpha$ , $\gamma$                | $3.3 \times 10^4$     | $7.3 \times 10^4$   | $2.3 \times 10^4$                          | Bone                               |
|                            | Pu 239  | $\alpha$ , $\gamma$                | $8.9 \times 10^4$     | $7.3 \times 10^4$   | $7.2 \times 10^4$                          | Bone                               |
|                            | Pu 240  | $\alpha$ , $\gamma$                | $2.4 \times 10^6$     | $7.3 \times 10^4$   | $7.1 \times 10^4$                          | Bone                               |
|                            | Pu 241  | $\alpha$ , $\beta^-$ , $\gamma$    | $4.8 \times 10^3$     | $7.3 \times 10^4$   | $4.5 \times 10^3$                          | Bone                               |
|                            | Pu 242  | $\alpha$                           | $1.4 \times 10^6$     | $7.3 \times 10^4$   | $7.3 \times 10^4$                          | Bone                               |
|                            | Po 210  | $\alpha$                           | 138.4                 | 60                  | 42                                         | Spleen                             |
| Potassium<br>(19)          | K 42    | $\beta^-$ , $\gamma$               | 0.52                  | 58                  | 0.52                                       | Total Body                         |
| Praseodymium<br>(59)       | Pr 142  | $\beta^-$ , $\gamma$               | 0.8                   | $1.5 \times 10^3$   | 0.8                                        | Bone                               |
|                            | Pr 143  | $\beta^-$                          | 13.7                  | $1.5 \times 10^3$   | 13.6                                       | Bone                               |
| Promethium<br>(61)         | Pm 147  | $\alpha$ , $\beta^-$               | 920                   | $1.5 \times 10^3$   | 570                                        | Bone                               |
|                            | Pm 149  | $\beta^-$ , $\gamma$               | 2.2                   | $1.5 \times 10^3$   | 2.2                                        | Bone                               |
| Protoactinium<br>(91)      | Pa 230  | $\alpha$ , $\beta^-$ , K, $\gamma$ | 17.7                  | $7.3 \times 10^4$   | 17.7                                       | Bone                               |
|                            | Pa 231  | $\alpha$ , $\beta^-$ , $\gamma$    | $1.3 \times 10^7$     | $7.3 \times 10^4$   | $7.3 \times 10^4$                          | Bone                               |
|                            | Pa 232  | $\beta^-$ , $\gamma$               | 27.4                  | $5.1 \times 10^4$   | 27.4                                       | Kidney                             |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay           | Half-life (days)           |                              |                   | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|-----------------------------------------|----------------------------|------------------------------|-------------------|-------------------------------------|------------------------------------|
|                            |         |                                         | Physical<br>T <sub>r</sub> | Biological<br>T <sub>b</sub> | Effective<br>T    |                                     |                                    |
| Radium<br>(88)             | Ra 223  | $\alpha$ , $\beta^-$ , $\gamma$         | 11.7                       | $1.64 \times 10^4$           | 11.7              | 0.05                                | Bone                               |
|                            | Ra 224  | $\alpha$ , $\beta^-$ , $\gamma$ , $e^-$ | 3.64                       | $1.64 \times 10^4$           | 3.64              | 0.06                                | Bone                               |
|                            | Ra 226  | $\alpha$ , $\beta^-$ , $\gamma$         | $5.9 \times 10^3$          | $1.64 \times 10^4$           | $1.6 \times 10^4$ | 0.10                                | Bone                               |
|                            | Ra 228  | $\alpha$ , $\beta^-$ , $\gamma$ , $e^-$ | $2.4 \times 10^3$          | $1.64 \times 10^4$           | $2.1 \times 10^3$ | 0.06                                | Bone                               |
| Radon<br>(86)              | Rn 220  | $\alpha$ , $\beta^-$ , $\gamma$ , $e^-$ | -                          | -                            | -                 | -                                   | -                                  |
|                            | Rn 222  | $\alpha$ , $\beta$ , $\gamma$           | 3.83                       | -                            | -                 | -                                   | -                                  |
| Rhenium<br>(75)            | Re 183  | K, $\gamma$                             | 73                         | 7                            | 6.4               | 80                                  | Total Body                         |
|                            | Re 186  | $\beta^-$ , $\gamma$                    | 3.79                       | 3                            | 1.7               | 20                                  | Thyroid                            |
|                            | Re 187  | $\beta^-$                               | $1.8 \times 10^{13}$       | 25                           | 25                | 300                                 | Skin                               |
|                            | Re 188  | $\beta^-$ , $\gamma$                    | 0.71                       | 3                            | 0.57              | 7                                   | Thyroid                            |
| Rhodium<br>(45)            | Rh 103m | $\gamma$ , $e^-$                        | 0.038                      | 28                           | 0.038             | 200                                 | Kidney                             |
|                            | Rh 105  | $\beta^-$ , $\gamma$                    | 1.52                       | 28                           | 1.44              | 40                                  | Kidney                             |
| Rubidium<br>(37)           | Rb 86   | $\beta^-$ , $\gamma$                    | 18.6                       | 60                           | 14.3              | 30                                  | Pancreas                           |
|                            | Rb 87   | $\beta^-$                               | $1.8 \times 10^{13}$       | 60                           | 60                | 200                                 | Pancreas                           |
| Ruthenium<br>(44)          | Ru 97   | K, $\gamma$ , $e^-$                     | 2.8                        | 2.5                          | 1.3               | 30                                  | Kidney                             |
|                            | Ru 103  | $\beta^-$ , $\gamma$ , $e^-$            | 41                         | 2.5                          | 2.4               | 20                                  | Kidney                             |
|                            | Ru 105  | $\beta^-$ , $\gamma$ , $e^-$            | 0.19                       | 2.5                          | 0.18              | 2                                   | Kidney                             |
|                            | Ru 106  | $\beta^-$ , $\gamma$                    | 365                        | 2.5                          | 2.48              | 3                                   | Kidney                             |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay | Half-life (days)      |                         |                        | MPBB<br>(body burden)<br>( $\mu\text{c}$ ) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|-------------------------------|-----------------------|-------------------------|------------------------|--------------------------------------------|------------------------------------|
|                            |         |                               | Physical<br>$T_{1/2}$ | Biological<br>$T_{1/2}$ | Effective<br>$T_{1/2}$ |                                            |                                    |
| Samarium<br>(62)           | Sm 147  | $\alpha$                      | $4.8 \times 10^{13}$  | $1.5 \times 10^3$       | $1.5 \times 10^3$      | 0.1                                        | Bone                               |
|                            | Sm 151  | $\beta^-$ , $\gamma$          | $3.7 \times 10^4$     | $1.5 \times 10^3$       | $1.4 \times 10^3$      | 100                                        | Bone                               |
|                            | Sm 153  | $\beta^-$ , $\gamma$          | 1.96                  | 187                     | 1.94                   | 20                                         | Liver                              |
| Scandium<br>(21)           | Sc 46   | $\beta^-$ , $\gamma$          | 85                    | 36                      | 25                     | 10                                         | Liver                              |
|                            | Sc 47   | $\beta^-$ , $\gamma$          | 3.43                  | 36                      | 3.1                    | 50                                         | Liver                              |
|                            | Sc 48   | $\beta^-$ , $\gamma$          | 1.83                  | 30                      | 1.7                    | 9                                          | Total Body                         |
|                            | Se 75   | K, $\gamma$                   | 127                   | 11                      | 10.1                   | 90                                         | Kidney                             |
| Selenium<br>(34)           | Si 31   | $\beta^-$ , $\gamma$          | 0.11                  | 60                      | 0.11                   | 10                                         | Lung                               |
| Silver<br>(47)             | Ag 105  | K, $\gamma$                   | 40                    | 5                       | 4.4                    | 30                                         | Total Body                         |
| Sodium<br>(11)             | Ag 110m | $\beta^-$ , $\gamma$          | 270                   | 10                      | 10                     | 10                                         | Kidney                             |
|                            | Ag 111  | $\beta^-$ , $\gamma$          | 7.5                   | 10                      | 4                      | 20                                         | Kidney                             |
|                            | Na 22   | $\beta^+$ , $\gamma$          | 950                   | 11                      | 11                     | 10                                         | Total Body                         |
| Strontium<br>(38)          | Na 24   | $\beta^-$ , $\gamma$          | 0.63                  | 11                      | 0.6                    | 7                                          | Total Body                         |
|                            | Sr 85m  | K, $\gamma$                   | 0.049                 | $1.3 \times 10^4$       | 0.049                  | 50                                         | Total Body                         |
|                            | Sr 85   | K, $\gamma$                   | 65                    | $1.3 \times 10^4$       | 64.7                   | 60                                         | Total Body                         |
|                            | Sr 89   | $\beta^-$                     | 50.5                  | $1.8 \times 10^4$       | 50.4                   | 4                                          | Bone                               |
|                            | Sr 90   | $\beta^-$                     | $1 \times 10^4$       | $1.8 \times 10^4$       | $6.4 \times 10^3$      | 2                                          | Bone                               |
|                            | Sr 91   | $\beta^-$ , $\gamma$          | 0.4                   | $1.8 \times 10^4$       | 0.4                    | 3                                          | Bone                               |
|                            | Sr 92   | $\beta^-$ , $\gamma$          | 0.11                  | $1.8 \times 10^4$       | 0.11                   | 2                                          | Bone                               |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay | Half-life (days)  |                  |                | MPBB<br>(body burden)<br>( $\mu$ c) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|-------------------------------|-------------------|------------------|----------------|-------------------------------------|------------------------------------|
|                            |         |                               | Physical<br>Tr    | Biological<br>Tb | Effective<br>T |                                     |                                    |
| Sulfur<br>(16)             | S 35    | $\beta^-$                     | 87.1              | 623              | 76.4           | 90                                  | Testis                             |
| Tantalum<br>(73)           | Ta 182  | $\beta^-, \gamma$             | 112               | 400              | 88             | 7                                   | Liver                              |
| Technetium<br>(43)         | Tc 96m  | K, $\gamma$ , $e^-$           | 0.036             | 20               | 0.036          | 60                                  | Kidney                             |
|                            | Tc 96   | K, $\gamma$                   | 4.3               | 20               | 3.5            | 10                                  | Kidney                             |
|                            | Tc 97m  | K, $\gamma$ , $e^-$           | 92                | 20               | 16             | 20                                  | Kidney                             |
|                            | Tc 97   | K                             | $3.7 \times 10^6$ | 20               | 20             | 60                                  | Kidney                             |
|                            | Tc 99m  | $\beta^-, \gamma$             | 0.25              | 1                | 0.2            | 200                                 | Total Body                         |
|                            | Tc 99   | $\beta^-$                     | $7.7 \times 10^7$ | 20               | 20             | 10                                  | Kidney                             |
|                            | Te 125m | $\gamma$ , $e^-$              | 58                | 30               | 20             | 20                                  | Testis                             |
| Tellurium<br>(52)          | Te 127m | $\beta^-, \gamma$ , $e^-$     | 105               | 30               | 23             | 7                                   | Kidney                             |
|                            | Te 127  | $\beta^-$                     | 0.39              | 30               | 0.39           | 20                                  | Kidney                             |
|                            | Te 129m | $\beta^-, \gamma$ , $e^-$     | 33                | 30               | 16             | 3                                   | Kidney                             |
|                            | Te 129  | $\beta^-, \gamma$ , $e^-$     | 0.051             | 30               | 0.051          | 5                                   | Kidney                             |
|                            | Te 131m | $\beta^-, \gamma$ , $e^-$     | 1.25              | 30               | 1.2            | 4                                   | Kidney                             |
|                            | Te 132  | $\beta^-, \gamma$ , $e^-$     | 3.2               | 30               | 2.6            | 3                                   | Kidney                             |
|                            | Tb 160  | $\beta^-, \gamma$             | 73                | $1 \times 10^3$  | 68             | 20                                  | Bone                               |
| Terbium<br>(65)            |         |                               |                   |                  |                |                                     |                                    |
| Thallium<br>(81)           | Tl 200  | K, $\gamma$                   | 1.13              | 7                | 0.97           | 40                                  | Kidney                             |
|                            | Tl 201  | K, $\gamma$ , $e^-$           | 3                 | 7                | 2.1            | 40                                  | Kidney                             |
|                            | Tl 202  | K, $\gamma$ , $e^-$           | 12                | 7                | 4.4            | 20                                  | Kidney                             |
|                            | Tl 204  | $\beta^-$                     | $1.1 \times 10^3$ | 7                | 7              | 10                                  | Kidney                             |

| Element<br>(atomic number)    | Isotope    | Type of <sup>1</sup><br>Decay  | Half-life (days)     |                     |                   | MPBB<br>(body burden)<br>( $\mu\text{c}$ ) | Organ of <sup>2</sup><br>Reference |
|-------------------------------|------------|--------------------------------|----------------------|---------------------|-------------------|--------------------------------------------|------------------------------------|
|                               |            |                                | Physical<br>$T_r$    | Biological<br>$T_b$ | Effective<br>$T$  |                                            |                                    |
| Thorium<br>(90)               | Th 227     | $\alpha, \beta^-, \gamma$      | 18.4                 | $7.3 \times 10^4$   | 18.4              | 0.02                                       | Bone                               |
|                               | Th 228     | $\alpha, \beta^-, \gamma, e^-$ | 700                  | $7.3 \times 10^4$   | 693               | 0.02                                       | Bone                               |
|                               | Th 230     | $\alpha, \gamma$               | $2.9 \times 10^7$    | $7.3 \times 10^4$   | $7.3 \times 10^4$ | 0.05                                       | Bone                               |
|                               | Th 231     | $\alpha, \beta^-, \gamma$      | 1.07                 | $7.3 \times 10^4$   | 1.07              | 30                                         | Bone                               |
|                               | Th 232     | $\alpha, \beta^-, \gamma, e^-$ | $5.1 \times 10^{12}$ | $7.3 \times 10^4$   | $7.3 \times 10^4$ | 0.04                                       | Bone                               |
|                               | Th natural | $\beta, \beta^-, \gamma, e^-$  | $5 \times 10^{12}$   | $4 \times 10^4$     | $4.3 \times 10^4$ | 0.01                                       | Bone                               |
| Thulium<br>(69)               | Th 234     | $\beta^-, \gamma$              | 24.1                 | $7.3 \times 10^4$   | 24.1              | 4                                          | Bone                               |
|                               | Tm 170     | $\beta^-, K, \gamma, e^-$      | 127                  | $1 \times 10^3$     | 113               | 9                                          | Bone                               |
|                               | Tm 171     | $\beta^-$                      | 694                  | $1 \times 10^3$     | 410               | 90                                         | Bone                               |
| Tin<br>(50)                   | Sn 113     | $K, \gamma, e^-$               | 112                  | 100                 | 53                | 30                                         | Bone                               |
|                               | Sn 125     | $\beta^-, \gamma, e^-$         | 9.5                  | 100                 | 8.7               | 7                                          | Bone                               |
| Tungsten<br>(Wolfram)<br>(74) | W 181      | $K, \gamma$                    | 140                  | 4                   | 3.9               | 70                                         | Liver                              |
|                               | W 185      | $\beta^-$                      | 74                   | 9                   | 8                 | 30                                         | Bone                               |
|                               | W 187      | $\beta^-, \gamma$              | 1                    | 1                   | 0.5               | 30                                         | Total Body                         |
| Uranium<br>(92)               | U 230      | $\alpha, \beta^-, \gamma$      | 20.8                 | 300                 | 19.5              | 0.007                                      | Bone                               |
|                               | U 232      | $\alpha, \beta^-, \gamma, e^-$ | $2.7 \times 10^4$    | 300                 | 300               | 0.01                                       | Bone                               |
|                               | U 233      | $\alpha, \gamma$               | $5.9 \times 10^7$    | 300                 | 300               | 0.05                                       | Bone                               |
|                               | U 234      | $\alpha, \gamma$               | $9.1 \times 10^7$    | 300                 | 300               | 0.05                                       | Bone                               |
|                               | U 235      | $\alpha, \beta^-, \gamma$      | $2.6 \times 10^{11}$ | 15                  | 15                | 0.03                                       | Kidney                             |
|                               | U 236      | $\alpha, \gamma$               | $8.7 \times 10^9$    | 300                 | 300               | 0.06                                       | Bone                               |
|                               | U 238      | $\alpha, \gamma, e^-$          | $1.6 \times 10^{12}$ | 15                  | 15                | 0.005                                      | Kidney                             |

| Element<br>(atomic number) | Isotope | Type of <sup>1</sup><br>Decay | Half-life (days)  |                     | MPBB<br>(body burden)<br>( $\mu\text{c}$ ) | Organ of <sup>2</sup><br>Reference |
|----------------------------|---------|-------------------------------|-------------------|---------------------|--------------------------------------------|------------------------------------|
|                            |         |                               | Physical<br>$T_r$ | Biological<br>$T_b$ |                                            |                                    |
| Vanadium<br>(23)           | V 48    | $\beta^+$ , K, $\gamma$       | 16.1              | 74                  | 13.2                                       | Kidney                             |
| Xenon<br>(54)              | Xe 131m | $\gamma$ , $e^-$              | 12                | -                   | -                                          | -                                  |
|                            | Xe 133  | $\gamma$ , $e^-$              | 5.27              | -                   | -                                          | -                                  |
|                            | Xe 135  | $\beta^-$ , $\gamma$          | 0.38              | -                   | -                                          | -                                  |
| Ytterbium<br>(70)          | Yb 175  | $\beta^-$ , $\gamma$          | 4.1               | $1 \times 10^3$     | 4.1                                        | Bone                               |
| Yttrium<br>(39)            | Y 90    | $\beta^-$                     | 2.68              | $1.8 \times 10^4$   | 2.68                                       | Bone                               |
|                            | Y 91m   | $\beta^-$ , $\gamma$          | 0.035             | $1.8 \times 10^4$   | 0.035                                      | Bone                               |
|                            | Y 91    | $\beta^-$ , $\gamma$          | 58                | $1.8 \times 10^4$   | 58                                         | Bone                               |
|                            | Y 92    | $\beta^-$ , $\gamma$          | 0.15              | $1.8 \times 10^4$   | 0.15                                       | Bone                               |
|                            | Y 93    | $\beta^-$ , $\gamma$ , $e^-$  | 0.42              | $1.8 \times 10^4$   | 0.42                                       | Bone                               |
| Zinc<br>(30)               | Zn 65   | $\beta^+$ , K, $\gamma$       | 245               | 933                 | 194                                        | Total Body                         |
|                            | Zn 69m  | $\gamma$ , $e^-$ , $\beta^-$  | 0.58              | 14                  | 0.56                                       | Prostate                           |
| Zirconium<br>(40)          | Zr 69   | $\beta^-$                     | 0.036             | 14                  | 0.036                                      | Prostate                           |
|                            | Zr 93   | $\beta^-$ , $\gamma$ , $e^-$  | $4 \times 10^8$   | $1 \times 10^3$     | $1 \times 10^3$                            | Bone                               |
|                            | Zr 95   | $\beta^-$ , $\gamma$ , $e^-$  | 63.3              | 450                 | 55.5                                       | Total Body                         |
|                            | Zr 97   | $\beta^-$ , $\gamma$          | 0.71              | $1 \times 10^3$     | 0.71                                       | Bone                               |

<sup>1</sup> The organ of reference is the organ on which the body burden was calculated but is not necessarily the critical organ used to compute the permissible levels in air and water. The reader is referred to National Bureau of Standards Handbook No. 69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure," issued 5 June 1959 for a complete listing of critical organs and organs of reference.

## **APPENDIX B**

### **OPERATION OF RADIAC INSTRUMENTS**

This Appendix is composed of five sections which present descriptions and operating procedures for various radiac instruments. The radiacs are grouped according to the type of radiation measured.

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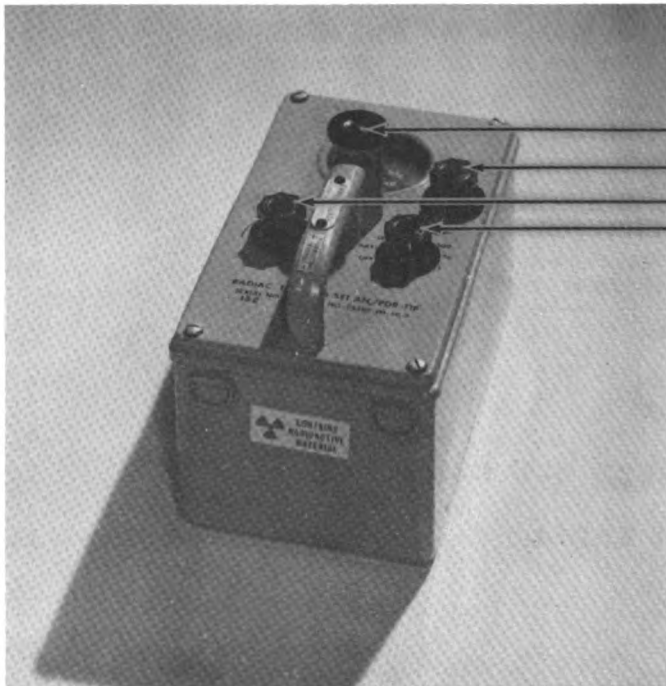
## APPENDIX B.1

### GAMMA RADIACS

#### INTRODUCTION

The two radiacs described below will measure only gamma or hard X rays since they have their detecting elements enclosed in a relatively thick metal case.

#### A. AN/PDR-39 (TIB)



- a. Meter Light Switch
- b. Source Check Switch
- c. Zero Adjustment Switch
- d. Range Selector Switch

#### RANGE

$\gamma$

- 0 - 5 mr/hr
- 0 - 50 mr/hr
- 0 - 500 mr/hr
- 0 - 5K mr/hr
- 0 - 50K mr/hr

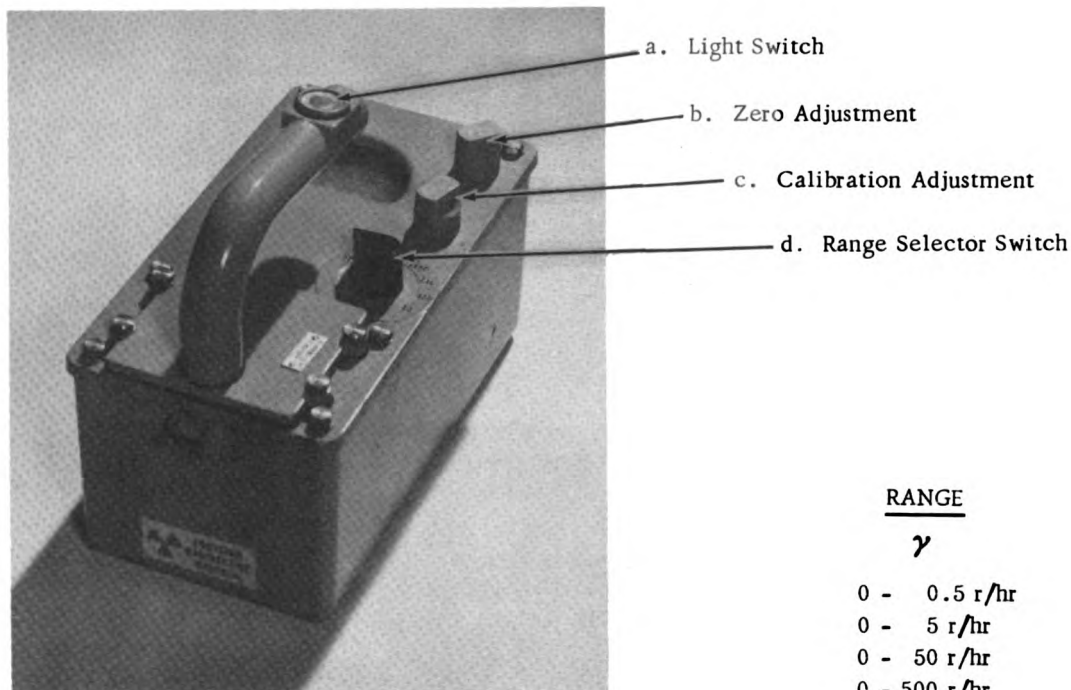
Description: The AN/PDR-39 (TIB) is an ionization chamber type radiac capable of measuring gamma or hard X rays (photons above 80 kev and no beta radiation). The ionization chamber is contained within the instrument's metal case. Maximum range is 50 r/hr. Range scales are 0-5, 0-50, 0-500, 0-5000, and 0-50,000 mr/hr. The numerals on the meter face change with the position of the range selector switch. The following controls are provided on the instrument:

1. Meter light switch (located on the carrying handle) which illuminates the meter face when depressed
2. Selector switch with OFF, BATT, and SET positions and 50K, 5K, 500, 50, and 5 mr/hr ranges
3. Zero adjustment switch
4. Source check switch.

Operation: Assuming the instrument is in working order and calibrated the following steps are taken to operate the instrument:

1. Turn the selector switch to BATT position. The meter pointer should fall within the white lines marked BATT. If it falls below this line, reject the instrument.
2. Turn the selector switch to the SET position. Allow a 2 minute warm-up, and rotate the zero switch until the pointer lies on zero.
3. Turn the range switch to each scale, noting that the scale on the meter face corresponds with selector switch position.
4. Turn the selector switch to the mr/hr range. Rotate the spring-loaded source-check switch  $1/2$  turn. This switch exposes a small radioactive source to the ionization chamber. The pointer on the meter should read 2.5 mr/hr or above.
5. If the instrument responds to the above checks and is calibrated, it may be used to measure penetrating X or gamma radiations. The zero position of the meter should be checked frequently by placing the range selector switch on SET and adjusting the zero position as necessary. (NEVER MOVE THE ZERO ADJUSTMENT SWITCH WITH THE RANGE SELECTOR SWITCH IN ANY POSITION OTHER THAN THE SET POSITION.)

## B. AN/PDR-18



**Description:** The AN/PDR-18 is a scintillation type radiac capable of measuring gamma or hard X rays (photons above 80 kev and no beta radiation). The scintillation crystal and associated electronic circuits are all contained in a single metal instrument case. Maximum range of the instrument is 500 r/hr. Range scales are 0-0.5, 0-5, 0-50, and 0-500 r/hr. The numerals on the meter face change with the position of the range selector switch. The following controls are provided on the instrument:

1. Meter light switch (on the carrying case handle) which illuminates the meter face when depressed
2. Selector switch with OFF, A, B, ZERO, and CAL positions and 500, 50, 5, and 0.5 r/hr ranges
3. Zero adjustment switch
4. Calibration control switch.

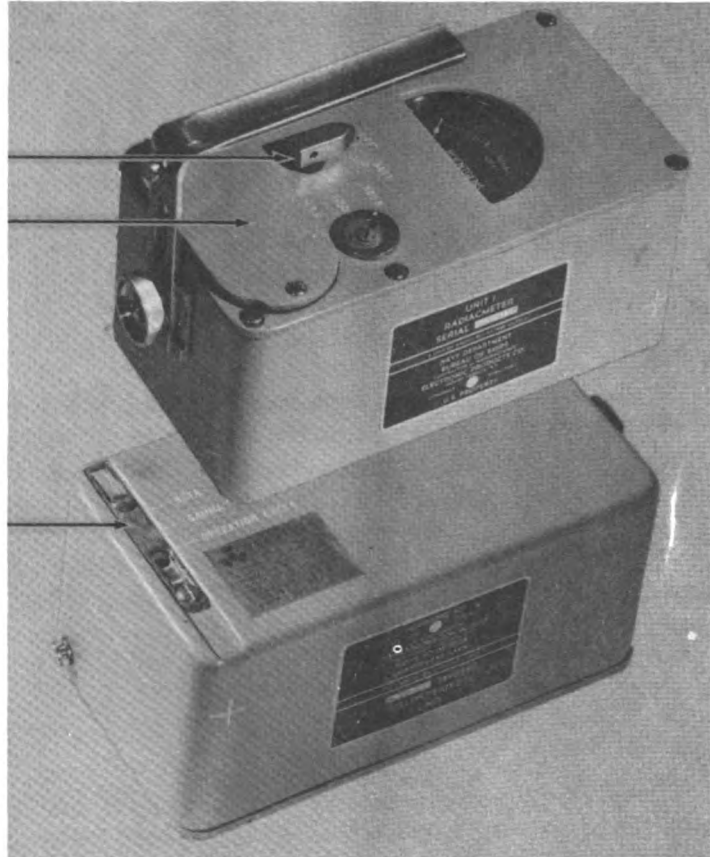
Operation: Assuming the instrument is in working order and calibrated, the following steps are taken to operate the instrument:

1. Turn the selector switch to the A position. The meter needle should move to the right of the A position on the meter scale. If this fails, replace the six flashlight batteries and repeat, or reject the instrument.
2. Turn the selector switch to the B position. The meter needle should move to the right of the B position marked on the meter face. Replace the batteries if this fails, and repeat the above procedure or reject the instrument.
3. Turn the selector switch to the ZERO position and adjust the zero control until the meter needle reads zero.
4. Place the selector switch in the CAL position and adjust the calibration control switch to make the meter needle read exactly full scale.
5. Repeat Steps 3 and 4.
6. Place the selector switch to the proper range for the dose rate to be measured.

## BETA-GAMMA RADIACS

The radiacs described below are capable of measuring beta and gamma radiations or hard X rays. The detecting chambers are so constructed that a window or shield may be placed over the chamber, thus stopping the beta radiation. The amount of beta or gamma radiation present is determined by subtracting the meter reading obtained with the shield in place from the reading with the shield open.

- a. Range Selector Switch
- b. Calibration Potentiometer Cover
- c. Function Selector Slide

 $\beta-\gamma$ 

0 - 500 r/hr  
0 - 50 r/hr  
0 - 5 r/hr

256

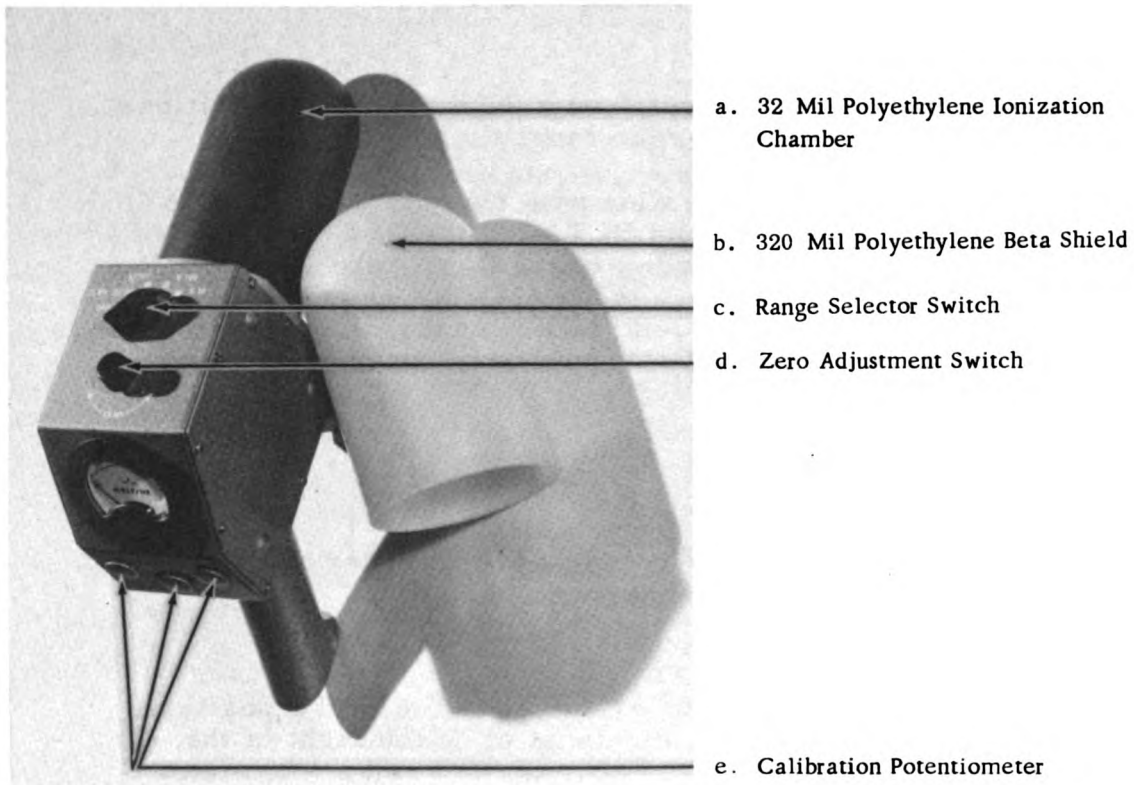
A 30  $\mu\text{c}$   $\text{Sr}^{90}$  source is contained on the function selector slide to check the instrument ranges for response to radiation. The numerals on the meter face change with the position of the range selector switch. The following controls are provided on the instrument:

1. A range selector switch with OFF and BATT positions and 500, 50, and 5 r/hr ranges
2. A function selector slide with the positions: OPERATION CHECK, GAMMA and BETA. In the OPERATION CHECK position the end-window of the G-M tube is exposed to a 30  $\mu\text{c}$   $\text{Sr}^{90}$  source. In the GAMMA position only gamma is detected by the G-M tube. At the BETA position the end-window of the G-M tube is exposed to beta and gamma radiations.

Operation: Assuming the instrument is in working order and calibrated, the following steps are taken to operate the instrument:

1. Turn the range selector switch to the BATT position. The meter should indicate at or to the right of the reference line located near the left end of the meter scale. If this fails, replace the batteries and repeat, or reject the instrument.
2. Place the function selector slide in the OPERATION CHECK position (to move slide, press down, slide and release). Turn the range selector switch to 500 r/hr range. Meter should deflect slightly. Turn to 50 r/hr range and meter should indicate over 3 r/hr. Turn to the 5 r/hr range and meter should indicate over 3 r/hr.
3. To measure gamma, place the function selector slide in the GAMMA position and place the range selector switch on most sensitive range on which the needle does not go off scale.
4. To detect beta, first take a reading with the function selector slide in the GAMMA position. Move the function selector slide to the BETA position and note the difference in reading. The difference is due to beta radiation. Response of the instrument to beta radiation is not stated in the manufacturer's instructions.

## B. CP-3DM "Cutie Pie"



### RANGE

#### **$\beta$ - $\gamma$**

- 0 - 100 mrep/hr
- 0 - 1,000 mrep/hr
- 0 - 10,000 mrep/hr
- 0 - 100,000 mrep/hr

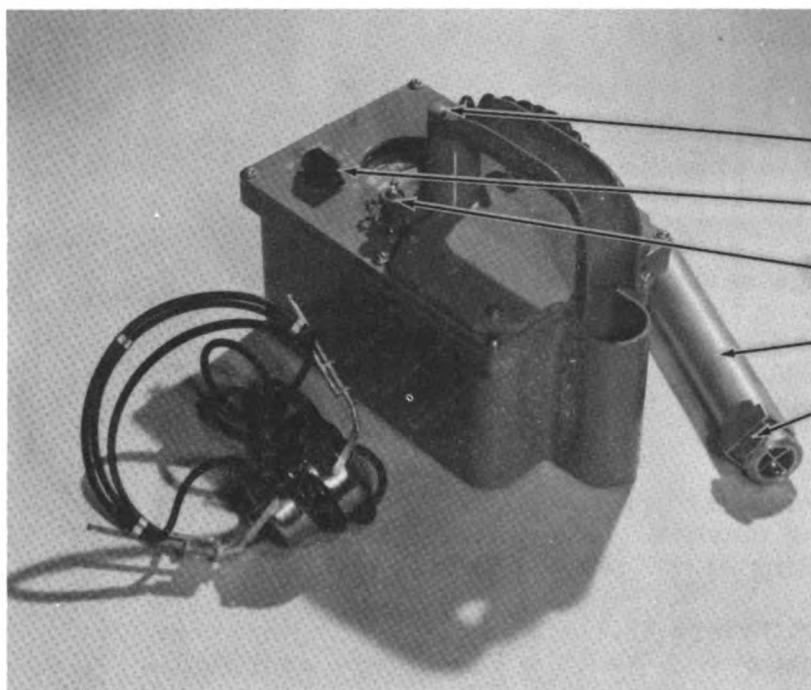
**Description:** The CP-3DM "Cutie Pie" is an ionization chamber type radiac. The ionization chamber consists of a central electrode sealed in an air atmosphere within a 1/32 inch polyethylene wall. A 1/4 inch thick molded polyethylene boot or shield is provided with the instrument to differentiate between beta and gamma radiations. The following controls are provided:

1. Zero adjustment switch
2. Range selector switch with OFF, and ZERO SET positions and 0-100, 0-1000, 0-10,000 and 0-100,000 mrep/hr beta-gamma ranges.

Operation: Assuming the instrument is in working order and calibrated, the following steps are taken to operate the instrument:

1. Turn the range selector switch to the ZERO SET position. Using the zero adjustment switch, set the meter needle to read ZERO. (NEVER MOVE ZERO ADJUSTMENT SWITCH WITH THE RANGE SELECTOR SWITCH IN ANY POSITION OTHER THAN THE SET POSITION.)
2. Turn the selector switch to the proper range. The meter reading must be multiplied by the X1, X10, X100, or X1000 setting of the range selector switch.
3. With the polyethylene shield in place, the instrument detects gamma only. With the shield removed, both beta and gamma are detected. The beta reading may be determined by subtracting the gamma reading from the beta-gamma reading. For general monitoring purposes, the beta reading is a relative indication of the true beta dose to within  $\pm 20\%$ .





- a. Meter Light Switch
- b. Range Switch
- c. Earphone Connection
- d. External Probe
- e. Beta Shield

RANGE

**$\beta$ - $\gamma$**

0 - 0.5 mr/hr

0 - 5 mr/hr

**$\gamma$**

0 - 50 mr/hr

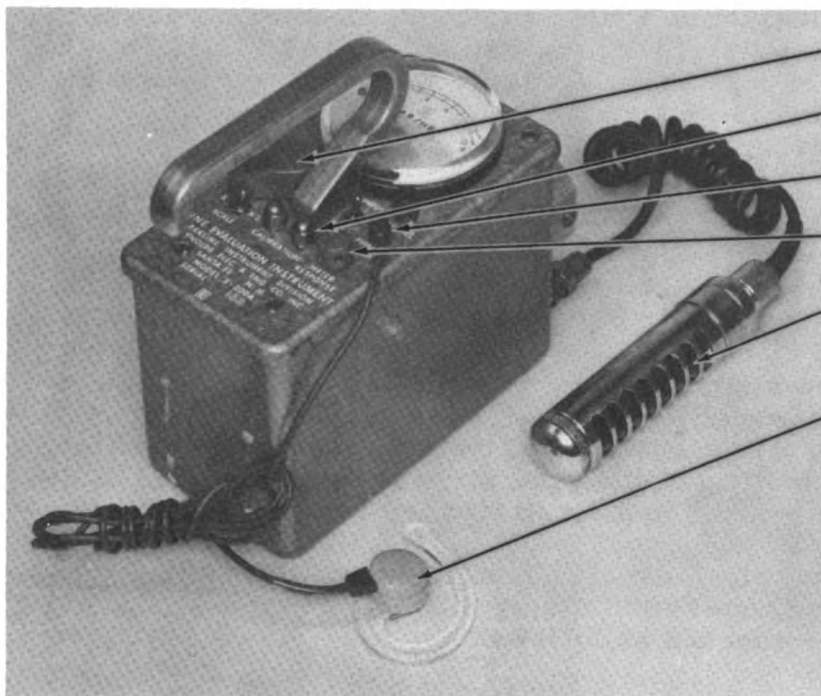
0 - 500 mr/hr

**Description:** The AN/PDR-27 series radiac is a Geiger-Mueller type radiac instrument. The instrument is housed in a metal case and has two G-M tubes. One tube is located in the carrying case above the dimple in the bottom of the case and operates only on the 0-500 and 0-50 mr/hr scales. The external probe contains the second tube, an end-window type G-M tube which operates only on the 0-0.5 and 0-5 mr/hr scales. This instrument is only sensitive to beta on the external probe when the beta shield is open. The window thickness of the end-window tube is 0.5 mil of mica, which is transparent to all beta particles greater than 0.05 Mev. The beta reading may be determined by subtracting the gamma reading (closed window) from the beta-gamma reading (open window) on only the 0-0.5 and 0-5 mr/hr scales. This instrument has a single switch, the range selector, with OFF, BATT CHECK, 500, 50, 5, and 0.5 mr/hr positions. The numerals on the meter face change with the position of the range selector switch. The AN/PDR-27 has an earphone jack, and the dial is illuminated by tilting the case approximately 30° with the meter end up or by depressing a button on the carrying handle in the case of Modification F and later models.

Operation: Assuming the instrument is in working order and calibrated, the following steps are taken to operate the instrument:

1. Turn the selector switch to the BATT CHECK position marked on the middle of the scale; the meter needle should go to or above mid-scale. If the needle does not go to at least mid-scale, reject the instrument or replace the batteries and repeat. (The BATT CHECK position checks only the filament batteries and does not ensure that the instrument will detect radiation.)
2. Turn the selector switch to the desired scale.  
(REMEMBER THE EXTERNAL PROBE DOES NOT OPERATE ON THE 0-500 OR 0-50 MR/HR SCALES.)
3. Check the instrument for response to radiation by exposing to a known source or a luminous dial wrist watch. Checking this instrument against an external source is the only method of determining if it will respond to radiation. A source in a plastic stick is provided with each instrument. The purple end of this plastic stick contains approximately 7  $\mu$ c of radioactive material, either radium or cobalt-60. Using this source, the AN/PDR-27 should be checked as follows:
  - a. With the purple end of source stick in case dimple and range selector switch on 500 mr/hr, the meter reading should be between 10 and 30 mr/hr.
  - b. With the purple end of source stick in case dimple and range selector switch on 50 mr/hr, the meter reading should be between 5 and 15 mr/hr.
  - c. With the probe in the carrying case well, the purple end of source stick at the top ridge of the well, and the range switch on 5 mr/hr, the meter reading should be between 1 and 3 mr/hr.
  - d. With the probe in the carrying case well, the purple end of the stick held away from the top ridge of the well, and the range on 0.5 mr/hr, the meter reading should be between 0.1 and 0.3 mr/hr.

#### D. EBERLINE MODEL E-112B G-M COUNTER



- a. Range Selector Switch
- b. Calibration Potentiometer
- c. Earphone Connection
- d. Meter Response Adjustment
- e. Constant-length  
Variable-width Probe
- f. Earphone

##### RANGE

**$\beta$ - $\gamma$**

- 0 - 0.2 mr/hr
- 0 - 2 mr/hr
- 0 - 20 mr/hr

**Description:** The Eberline Model E-112B is a side window Geiger-Mueller type radiac instrument. Its meter is marked off in twenty divisions from 0 to 20 in units of mr/hr. The instrument has a single range selector switch with OFF, X1, X0.1, and X0.01 positions. The meter reading must be multiplied by the setting of the range selector switch to obtain the mr/hr value. Earphones may be attached for use. A meter response adjustment control is provided which allows the time response of the meter to be continuously variable from 2 to 10 seconds. The external probe contains an aluminum wall Geiger tube with a wall thickness of about 50 milligrams per square centimeter. The G-M tube is housed in a metal probe with a side window that is constant in length but variable in width by rotating the shield. Beta particles may be stopped by closing the window area.

Operation: Assuming the instrument is in working order and calibrated, the following steps are taken to operate the instrument:

1. Turn the selector switch to each range scale and check for response to radiation by exposing the probe to a low level radiation source.
2. Insert the earphones and check for audio response. (Use 2000 ohm impedance phones since lower-impedance earphones will overload the circuit and reduce the value observed on the meter dial.)
3. Operate the instrument on the most sensitive range that will allow the meter to remain on scale.

## APPENDIX B. 3

### ALPHA-BETA-GAMMA RADIAC

#### INTRODUCTION

The radiac described below is capable of measuring the intensity of, and discriminating between, alpha, beta, and gamma radiations. This is accomplished by use of an ion chamber detector and a combination of shields. Such instruments appear to be ideal at first glance and find many applications, but are limited by the fact that the sensitivity for alpha is generally low if the gamma range is high, with a low gamma range if the alpha sensitivity is high. Detection of alpha is also hampered if gamma or beta radiations are present.

#### A. "JUNO"

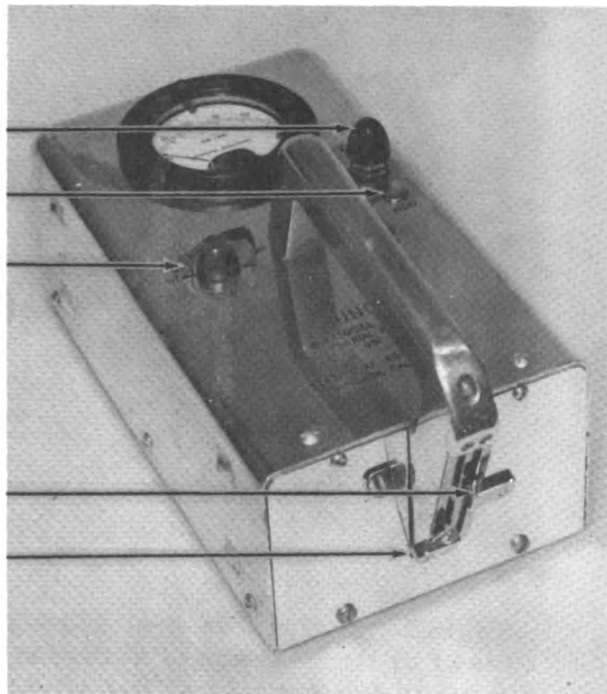
- a. Zero Adjustment
- b. Calibration Potentiometer
- c. Range Selector Switch

- d. Shield Control
- e. Shield Control

#### RANGE

#### **$\alpha$ - $\beta$ - $\gamma$**

- 0 - 50 mr/hr
- 0 - 500 mr/hr
- 0 - 5,000 mr/hr



**Description:** The JUNO is an ionization chamber type radiac, manufactured by Technical Associates, which is capable of measuring and discriminating between alpha, beta, and gamma radiations. Sliding shields of .01 inch cellulose acetate sheet and 0.1 inch aluminum are used in conjunction with the 0.45 mg/cm<sup>2</sup> rubber hydrochloride window

on the ionization chamber. The following controls are provided:

1. A zero adjustment switch
2. Range selector switch with OFF, ON, SET positions and 50, 500, and 5000 mr/hr alpha-beta-gamma ranges
3. Shield controls located on the handle.

Operation: Assuming the instrument is in working order and calibrated, the following steps are used to operate the instrument:

1. Turn the range selector switch to the ON position and wait five seconds for the electrometer tube filament to warm up.
2. Turn the selector switch to the SET position and adjust the ZERO adjustment control until the meter reads exactly zero.
3. Turn the selector switch to the "X1" position. If the meter reads off scale the radiation present is greater than 50 mr/hr and the selector switch should be turned to either the "X10" or "X100" position.
4. If all shields are closed the instrument will measure only gamma radiation. To read beta radiation, open the aluminum shield (control on handle marked G). Subtract the shields-closed reading from this reading to obtain beta. To determine alpha radiation, open the cellulose acetate shield (control on handle marked B). Subtract the reading obtained with the G shield open from this reading and multiply the net mr/hr by  $2000 \text{ d/m}/80 \text{ cm}^2/\text{mr/hr}$ . The result is an approximate d/m value of the alpha present per  $80 \text{ cm}^2$ .
5. As for all instruments, the individual unit must be calibrated to determine the response to any type of radiation.

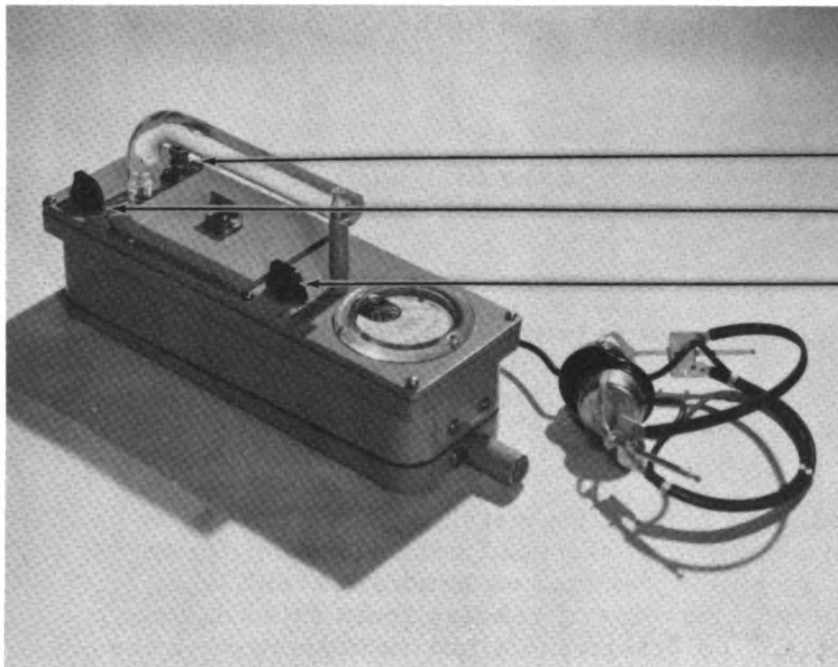
## APPENDIX B.4

### ALPHA RADIACS

#### INTRODUCTION

The alpha particle is a relatively large nuclear particle and consequently has a small range in matter. A piece of tissue paper will stop an alpha particle. The range in air of a 4 Mev alpha particle is about 2.5 cm. Alpha radiacs are usually proportional counters driving count-rate meter circuits. Such radiacs must have a thin window (1 mg/cm<sup>2</sup> of aluminized mylar) to pass the alpha particles. Three alpha radiacs are described below.

#### A. AN/PDR-10



- a. Earphone Connection
- b. Discharge Switch
- c. Main Selector Switch

RANGE

**$\alpha$**

0 - 10,000 d/m/150 cm<sup>2</sup>

Description: The AN/PDR-10 is an air proportional alpha radiac with the detector on the bottom of the case. The meter face is a compressed scale going from 0 to 10 and is labelled to read the d/m x 1000 for the 150 cm<sup>2</sup> window surface area. The controls consist of a main selector switch and a discharge switch. The main selector switch has the CHG (charge) OFF, BATT COND, and READ positions. The discharge switch is spring-loaded and must be held in position to function.

Operation: Assuming the instrument is in operating order and calibrated, the following steps are taken to operate the instrument:

1. Turn the main selector switch to BATT COND and observe the meter indication. If it is above the BATT mark on the meter face, the batteries are in satisfactory condition. If not, replace the batteries or reject the instrument.
2. Attach the head set (earphones).
3. Turn the main selector switch to the CHG position for about five seconds.
4. Turn the main selector switch to READ and eliminate the corona discharge or rapid counting by operating the discharge switch until the hiss and rapid counting are no longer heard in the head set. The discharge switch should not be operated once the initial rapid counting has been eliminated. When the instrument is at the proper operating voltage, about three clicks per minute will be heard in the earphones.
5. Some models of the AN/PDR-10 series radiacs are equipped with a protective cover for the counting chamber. This cover must be removed from the counting chamber before alpha radiation can be detected. With the protective cover on the counting chamber removed, place the instrument directly over, but not touching, a calibrated alpha source. Distance above the source should be about 1/4 to 1/2 inch. A series of calibrated sources of the order 100, 500, 1000, 5000, and 10,000 disintegrations per minute should be used. The meter should indicate the value of the source being measured if the internal calibration adjustments have been properly set. If the radiac is operating but the meter value differs from the source value, it is still usable and may be calibrated by comparing the meter reading on an unknown source with that of a known standard. (Example: the meter reads 4000 d/m/150 cm<sup>2</sup> on an unknown source. When compared to a calibrated source of 5000 d/m, the meter reads 2500 d/m/150 cm<sup>2</sup> or one-half of the true value. Then the measured value



of the unknown source must be multiplied by 2. Value of unknown source is  $4000 \times 2$  or  $8000 \text{ d/m/150 cm}^2$ .) When a reading is to be taken, the manufacturer recommends that the instrument be held at the point of interest for about one minute or more to allow the meter to come to equilibrium.

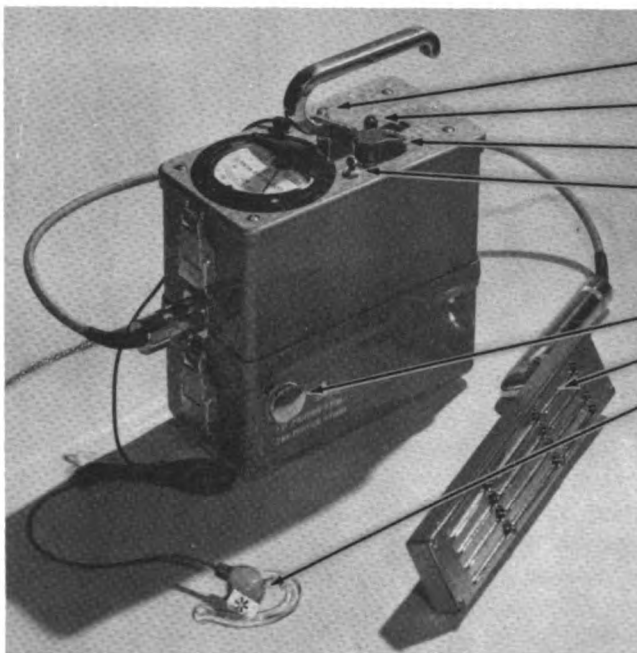
6. The AN/PDR-10 series radiac is slightly sensitive to beta and gamma radiation. The effect of beta or gamma radiation on the instrument may be determined by placing it in a known gamma field and noting the meter reading for a given exposure rate. In a field situation, the effect of beta and gamma radiations on the instrument may be determined by placing the instrument over the source or area in question and noting the meter indication; then determine the meter indication due to alpha by sliding a piece of uncontaminated paper between the surface being measured and the counting chamber. Since alpha radiations cannot penetrate the paper, any indication on the instrument meter is due to beta or gamma radiations.
7. The charging procedure described in Steps 3 and 4 must be repeated approximately once every 30 minutes. A calibration check against a standard source should be made periodically during monitoring.

**Note:** The range of the AN/PDR-10 may be extended by masking off a portion of the counting chamber. It is necessary to recalibrate the instrument if such modifications are made. In use or modification of the instrument, care should be taken to prevent damaging the delicate window of the detector.



The RAS-10 being developed by the U. S. Naval Radiological Defense Laboratory is an alpha radiac employing a photomultiplier tube with an aluminum-covered zinc-sulphide detector. The sensitive area of the probe consists of six slots with a total of  $17 \text{ cm}^2$  sensitive area distributed over a probe area of  $60 \text{ cm}^2$ . The instrument has an apparent efficiency of approximately 50% , producing an effective range of  $2 \times 10^6 \text{ d/m/17 cm}^2$ .

## B. AN/PDR-54, EBERLINE MODEL PAC 3-G



- a. Discriminator Potentiometer
- b. High Voltage Potentiometer
- c. Range Selector Switch
- d. Meter Reset Button
- e. Gas Flow Control
- f. Alpha Probe
- g. Earphone

### RANGE

**$\alpha$**

- 0 - 1,000 c/m/60 cm<sup>2</sup>
- 0 - 10,000 c/m/60 cm<sup>2</sup>
- 0 - 100,000 c/m/60 cm<sup>2</sup>

**Description:** The AN/PDR-54, PAC 3-G\* alpha radiac, manufactured by the Eberline Instrument Division of Reynolds Electrical and Engineering Company, uses a propane gas proportional alpha counter with an integrating count-rate-meter circuit. (A similar instrument is manufactured without the gas flow feature.) The gas proportional instrument consists of a carrying case housing the electronic circuit, batteries, and propane gas bottle, with an external probe of 60 cm<sup>2</sup> surface area. The carrying case is divided into two sections. The upper section of the case contains the electronic components, the meter graduated from 0 to 1000 c/m, a range selector switch, a meter reset button, an earphone receptacle, and a receptacle for the probe lead and gas supply. An internal calibration adjustment is provided for each range of the instrument. The lower section of the case carries a bottle of compressed propane gas and the flow control valves. The probe of the instrument has a window area of 60 cm<sup>2</sup> with a 0.85 mg/cm<sup>2</sup> mylar window. Gas flow to the probe is controlled by operation of a two position valve. The flush position for clearing air from the probe is used during warm-up of the instrument. For operation, the valve is placed in the "run" position which allows a factory preset amount of gas to flow through the chamber.

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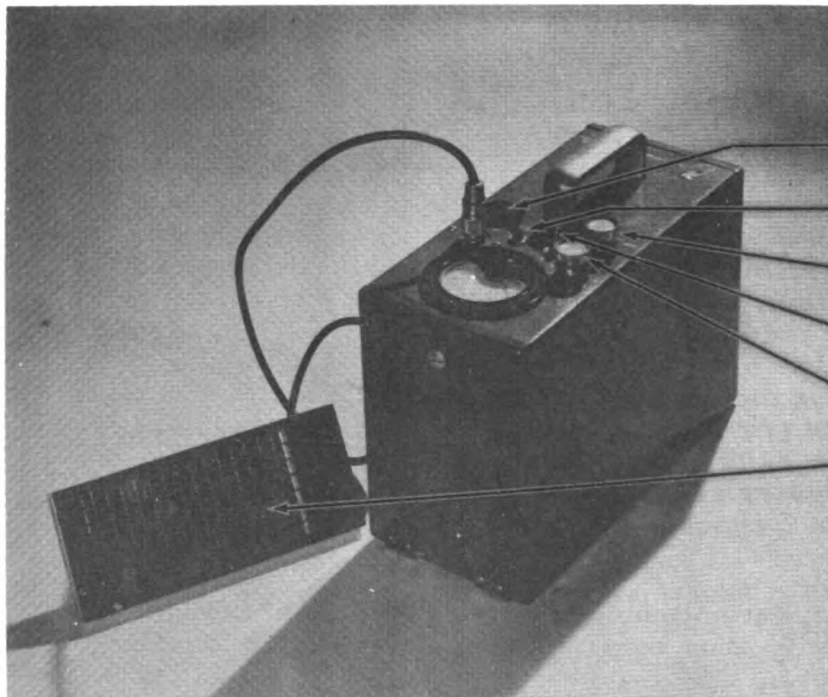
\*The AN/PDR-54, PAC 3-GN is the same instrument as the PAC 3-G but uses standard military earphones and has a dustproof meter reset button.

**Operation:** Assuming the instrument is in working order, the following steps are taken to operate the instrument:

1. With the proportional counting probe attached, turn the range-scale selector switch to the desired scale and pull the gas flow valve full out. After about two minutes, close the gas flow valve to run position. The probe is now completely flushed of air, and the instrument is ready for use.
2. The instrument is factory-calibrated with a point source to read in counts per minute at 50% geometry. To check this calibration, place the probe at a distance of not greater than 1/4 inch above a known point source of alpha radiation, such as plutonium, polonium, etc., and observe the meter reading. The meter should indicate one-half of the d/m value of the source. To determine d/m from the meter reading, multiply the meter reading in counts per minute by the scale-multiplying factor X1, X10, or X100, and then multiply this value by 2. (Example: Meter reading 400 c/m on X10 scale equals 4000 c/m x 2 equals 8000 d/m.)
3. The meter reset button, when depressed, will return the meter to 0, thus zeroing the instrument for another reading.

**Note:** The range of the PAC 3-G may be extended by masking off a portion of the counting probe. It is necessary to recalibrate the instrument if such modifications are made.

### C. NUCLEAR CHICAGO "PEE WEE" MODEL 2111



- a. Earphone Connection
- b. Meter Reset Button
- c. Range Selector Switch
- d. High Voltage Switch
- e. Pulse Height Selector
- f. Alpha Probe

#### RANGE

##### **$\alpha$**

- 0 - 2,000 c/m/75 cm<sup>2</sup>
- 0 - 20,000 c/m/75 cm<sup>2</sup>

**Description:** The "Pee Wee" Model 2111, manufactured by the Nuclear Instrument Corporation is an alpha radiac consisting of an external probe and a carrying case. The alpha probe is an air proportional detector with an open window face area of 75 cm<sup>2</sup>.

The "Pee Wee" carrying case contains a meter graduated from 0 to 20, a high-voltage ON and OFF switch, a pulse-height selector switch, a meter reset switch, a probe connector receptacle, a plug for earphones, and a range selector switch. The range selector switch contains three positions: OFF, X100, and X1000.

**Operation (Alpha Detection):** Assuming the instrument is in working order , the following steps are taken to operate the instrument:

1. Turn the range selector switch to the X100 position after connecting the alpha probe.
2. Turn the high-voltage switch to the ON position.
3. Place the probe 1/4 inch above a source of known d/m value. Note the meter reading and adjust the pulse-height selector (phs) switch for 50% geometry. (A 5000 d/m standard source should read 2500 c/m.)
4. Remove the alpha source and place the probe in a beta field of at least 100 mrad/hr or in a 50 mr/hr gamma field and note any reading on the meter or noise in the head set. Adjust the phs control toward 0 until there is no beta or gamma response. Redetermine the efficiency if the phs is different from that found in Step 3 above. Mark this setting on the instrument case and keep the phs switch at this value during all monitoring for alpha. If this reduces the efficiency to less than 25% , return the instrument for repair.
5. Place the probe over the alpha source again and note the response. List the meter reading for various d/m source values. In alpha monitoring, the meter reading can be converted to d/m by referring to this list and interpreting between values as necessary.
6. During monitoring, the meter readings may be returned to zero by depressing the reset button.

**Note:** The range of the "Pee Wee" may be extended by masking off a portion of the external probe. It is necessary to recalibrate the instrument if such modifications are made.

## **APPENDIX B. 5**

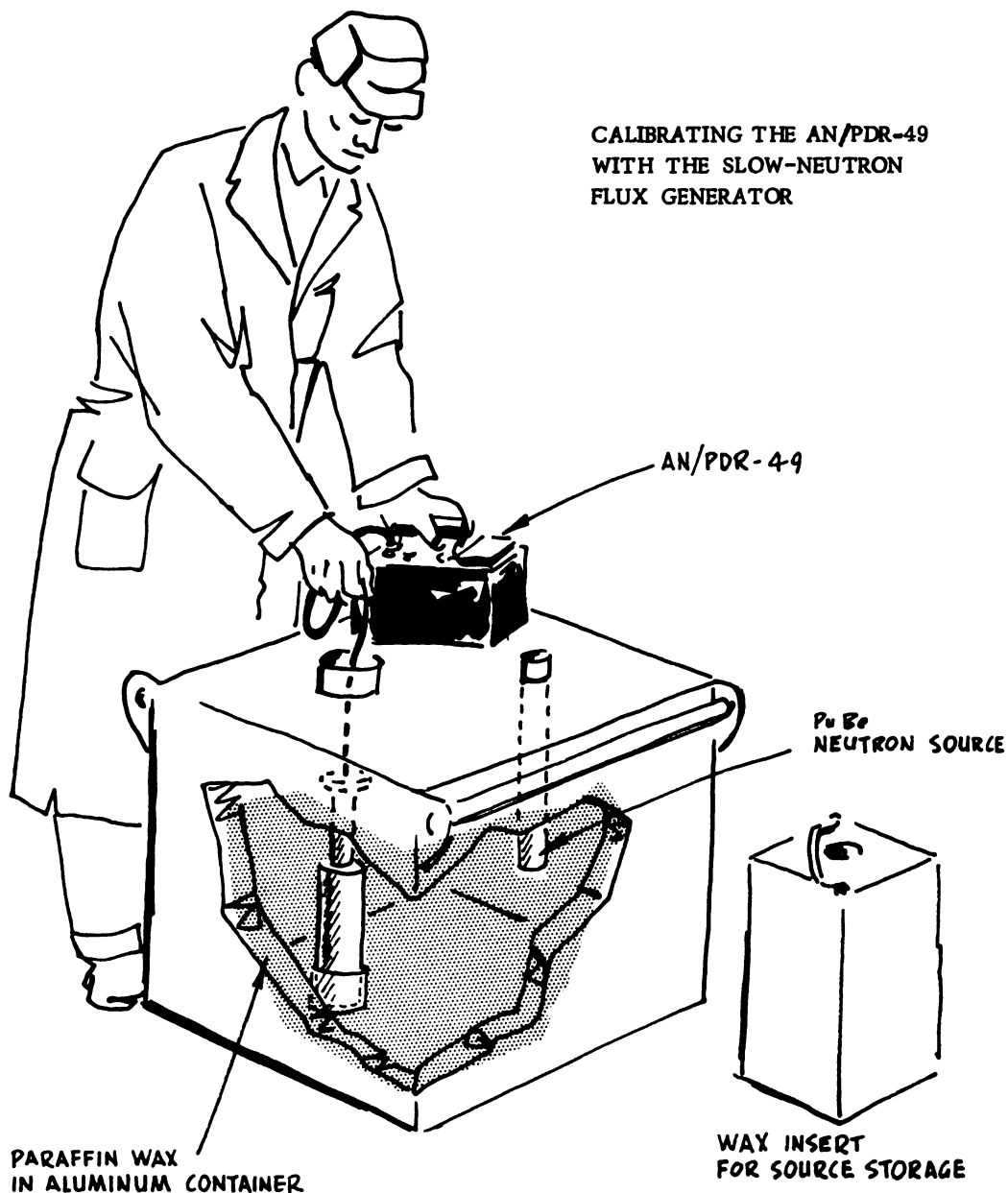
### **NEUTRON DETECTORS**

#### **INTRODUCTION**

Since the neutron is an uncharged particle and cannot be detected directly, neutron detectors depend upon a measurement of the secondary effects which result from nuclear interactions. For slow-neutron detection, the following two interactions are generally used: (1) absorption of the neutron by the nucleus with emission of a charged particle and (2) absorption of the neutron by the nucleus with the formation of a radionuclide. Fast-neutron detection is generally based upon the principle of elastic scattering, that is, a neutron colliding with a proton and transferring its momentum to the proton. The proton in turn then produces ionization which can be measured.

A common method of detecting slow neutrons is by use of a boron-filled ( $B^{10}$ ) counter operated in the proportional region. The absorption of a neutron by the  $B^{10}$  isotope results in the emission of an energetic alpha particle which can then be detected by its resultant ionization. Fast neutrons can be detected by slowing them down in a moderator, such as paraffin, and then counting the thermalized neutron with a boron-filled proportional counter.

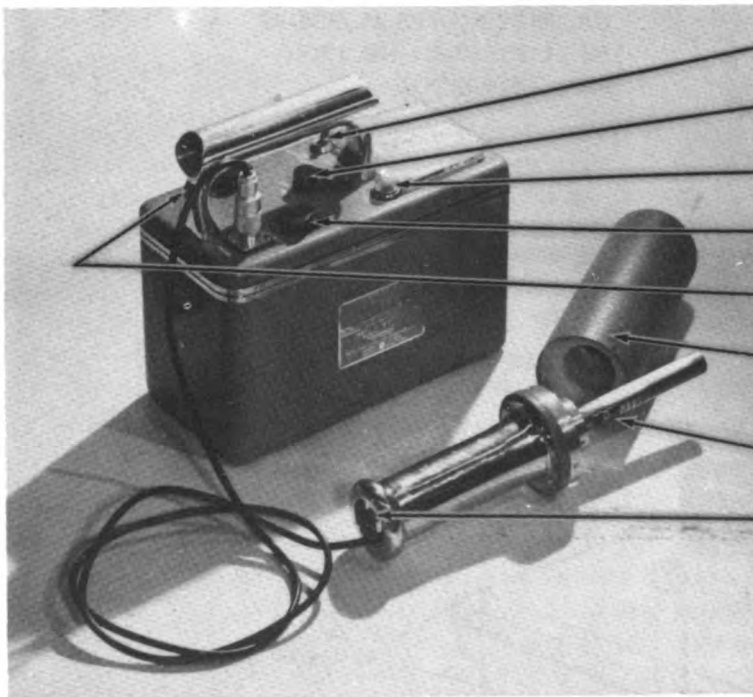
Since neutron radiacs do not differentiate between energies other than thermal and fast, the user must be careful in monitoring. The best procedure is to calibrate the detector against a known source of the same energy spectrum. The ranges of the instruments described in this section are taken from the manufacturer's data and generally apply to radium-beryllium or polonium-beryllium neutron spectrums. Pages 159 and 160 of Volume II contain additional information on neutron monitoring.



The Slow-Neutron Flux Generator pictured above provides a method of producing slow neutrons (fast neutrons interacting with paraffin wax) for calibration of the AN/PDR-49. With a suitable adaptor placed over the source tube, the AN/PDR-47 may also be checked for fast-neutron sensitivity.



## A. AN/PDR-49 (interim model) NEUTRON DETECTOR



- a. Meter Time-Constant Switch
- b. Range Selector Switch
- c. Neon Light
- d. Calibration Control
- e. Earphone Connection
- f. Cadmium-shielded Wax Moderator
- g.  $\text{BF}_3$  Tube
- h. Probe Control Switch

### RANGE

$\eta$  (slow or fast)

- 0 - 25,000 n/cm<sup>2</sup>/sec
- 0 - 2,500 n/cm<sup>2</sup>/sec
- 0 - 250 n/cm<sup>2</sup>/sec

**Description:** The AN/PDR-49 radiac consists of a carrying case and an external probe. The instrument is intended for general detection of neutron radiation.

For neutron detection the instrument uses a  $\text{BF}_3$  gas-filled chamber for proportional counting. The boron in the gas is enriched in the  $\text{B}^{10}$  isotope. Surrounding the  $\text{BF}_3$  tube is a cadmium-shielded wax moderator. The probe may be used as a thermal and slow-neutron detector by removing the cadmium shield and wax, or by exposing the bare  $\text{BF}_3$  tube to the neutron flux. Fast neutrons may be monitored with the cadmium shield and wax moderator over the probe. The probe contains two mercury batteries, a pre-amplifier, and a control switch in addition to the  $\text{BF}_3$  tube cadmium shield and wax moderator. The range of the instrument is about 25,000 neutrons/cm<sup>2</sup>/sec for a radium-beryllium neutron spectrum.

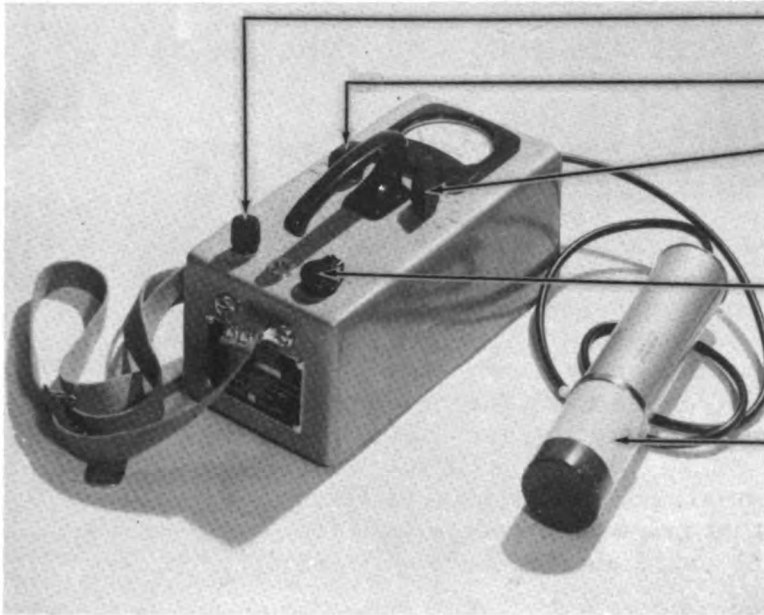
The carrying case contains a meter which indicates neutrons/cm<sup>2</sup>/sec from 0 to 250 and must be multiplied by the range selector setting. The following controls are provided on the carrying case:

1. Range selector switch with OFF, X100, X10, and X1 positions
2. Meter response switch with long (15 sec) and short (4 sec) time-constant positions
3. A receptacle for earphones
4. A receptacle for the probe lead
5. A calibration switch. (Should be in the full counterclockwise position before attaching the neutron probe. This controls a factory-set voltage for the BF<sub>3</sub> tube.)
6. Pilot-Light-Regulator. The neon lamp visible on the case indicates that power is applied and regulates the calibration of the unit independent of "B" battery voltage.

Operation: Assuming the instrument is in working order and calibrated for the energy of the neutrons to be detected, the following steps are required to operate the instrument:

1. With the range selector switch and probe control switch in the OFF position, connect the probe lead to the receptacle on the case.
2. Turn the range selector switch to the proper range and turn the detector switch to ON. Fast neutrons are detected with the moderator and shield on the BF<sub>3</sub> tube. The gamma response of the instrument should be determined. (The manufacturer indicates negligible response to a gamma flux of 5 r/hr from radium.) 60 c/m indicates a fast-neutron flux (Ra-Be neutron energies) of 10n/cm<sup>2</sup>/sec (according to the manufacturer).
3. When disconnecting the probe, it is recommended that the instrument stand for 3 min with the range selector and probe control switches off before disconnecting the probe lead.
4. The switch on the detector must be turned off as well as the range selector switch when securing the radiac.

## B. AN/PDR-47 (interim model) FAST-NEUTRON DETECTOR



- a. Zero Control
- b. Battery Switch
- c. Range Selector Switch
- d. Earphone Connection
- e. Proton-Recoil Proportional Counter

### RANGE

#### **Fast $\eta$**

- 0 - 500 mrep/hr
- 0 - 50 mrep/hr
- 0 - 5 mrep/hr
- INT (integrating)

**Description:** The AN/PDR-47 is a fast-neutron detecting radiac consisting of a carrying case and an external probe employing a proton-recoil proportional counter. The range of the radiac is 0 to 500 mrep/hr. The following controls are provided on the carrying case:

1. A battery switch with five positions: OFF, WAIT, ON, BATT CHECK 1, and BATT CHECK 2
2. A range switch with five positions "INT", "0", 500, 50, and 5
3. A zero control to zero the vacuum tube volt-meter circuit
4. A receptacle for earphones.

**Operation:** Assuming the instrument is in working order and calibrated for the energy of the neutrons to be detected, the following steps are required to operate the instrument:

1. Place the range switch in the "0" position.

2. Turn the battery switch to "WAIT". Leave in this position for 10 seconds or more.
3. Turn the battery switch to "ON".
4. Zero the meter with the zero control.
5. Turn the battery switch to the BATT CHECK 1 position and then to the BATT CHECK 2 position. If the meter reads less than 3 in either position, the unit should not be used until the batteries are replaced.
6. Return the battery switch to "ON" and check the zero of the meter.
7. Place the range switch on the proper scale (5, 50, or 500) and point the end of the probe toward the neutron source. The manufacturer recommends a 5 minute wait for a reading on the 5 range, 30 seconds on the 50 range, and a few seconds on the 500 range.
8. For readings lower than those readily readable on the 5 range, or for measurement of accumulated dose, place the range switch on the "INT" position and determine the time required for any given number of counts, preferably full scale, which is 200 counts. Dividing the accumulated count by the time in seconds gives mrep/hr exposure.
9. The instrument may be rezeroed at any time during the integrating measurement without disturbing the measurement. This is accomplished by placing the range switch on the "0" position and zeroing. Since the unit is NOT integrating over this time period, the time spent in zeroing should not be counted in the total integrating time.
10. If gamma radiation is present, the response of the instrument to gamma radiation should be known.

**( P O R A C C )**

## APPENDIX C

### REVIEW OF MATHEMATICS

This short review is designed to refresh the reader's memory concerning the more simple mathematical operations and problems which he will meet in radiological safety work.

#### EQUATIONS

To maintain the equality of the equation, perform the same operation on each side of the equation (i. e., do the same thing to each side). Thus each side may be multiplied or divided by the same quantity or the same quantity may be added to each side without changing the value of the equation.

To make use of this fundamental rule when solving equations, the following examples are given.

a. Given:  $D = I T$

To solve for T note that if I is removed from one side T will stand alone. This is accomplished by dividing both sides by I:

$$\frac{D}{I} = \frac{\cancel{I}T}{\cancel{I}}$$

$$\frac{D}{I} = T$$

or:  $T = \frac{D}{I}$  (Answer)

b. Given:  $I = \frac{D}{T}$

To solve for D multiply each side by T:

$$I T = \frac{D \cancel{T}}{\cancel{T}}$$

$$I T = D$$

or:  $D = I T$  (Answer)

c. Given:  $30 = 6 \times C \times 0.7$

To solve for C first multiply  $6 \times 0.7$  thus  
 $30 = 4.2 C$

Then divide each side by 4.2

$$\frac{30}{4.2} = \frac{4.2}{4.2} C$$

$$C = \frac{30}{4.2}$$

$$C = 7.14$$

or rounding off to two significant figures:

$$C = 7.1 \quad (\text{Answer})$$

## PROBLEMS

Try working problems given below. Check answers with those given on Page 289.

1.  $\frac{4}{(m-1)} = \frac{3}{(m-2)}$ ; solve for m.

2.  $(5x - 7) - (4x + 9) = (3x - 15) - (6x - 9)$ ; solve for x.

3.  $s(s-8) - 21 = 2s(s-13) - s(s-12)$ ; solve for s.

4.  $\frac{5w}{6} - \frac{3w}{4} = \frac{7w}{12} - \frac{13}{2}$ ; solve for w.

5.  $\frac{2s}{12} - 9 = \frac{2}{12} - 7s$ ; solve for s.

## NUMBERS EXPRESSED AS POWERS OF TEN

In the field of nuclear physics and radiological safety, very large and very small numbers are expressed by the use of ten raised to various powers.

Study the list given below.

|           |   |                                                                            |   |        |
|-----------|---|----------------------------------------------------------------------------|---|--------|
| $10^4$    | = | $10 \times 10 \times 10 \times 10$                                         | = | 10,000 |
| $10^3$    | = | $10 \times 10 \times 10$                                                   | = | 1,000  |
| $10^2$    | = | $10 \times 10$                                                             | = | 100    |
| $10^1$    | = | 10                                                                         | = | 10     |
| $10^0$    | = | 1                                                                          | = | 1      |
| $10^{-1}$ | = | $\frac{1}{10}$                                                             | = | 0.1    |
| $10^{-2}$ | = | $\frac{1}{10} \times \frac{1}{10}$                                         | = | 0.01   |
| $10^{-3}$ | = | $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10}$                     | = | 0.001  |
| $10^{-4}$ | = | $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10}$ | = | 0.0001 |

By use of this notation the numbers given below can be expressed in the concise form as shown below.

|                                  |   |                         |
|----------------------------------|---|-------------------------|
| 602,500,000,000,000,000,000      | = | $6.025 \times 10^{23}$  |
| 0.00000000000016                 | = | $1.6 \times 10^{-12}$   |
| 37,000,000,000                   | = | $3.7 \times 10^{10}$    |
| 0.000000000000000000000000006624 | = | $6.624 \times 10^{-27}$ |

When numerical problems are worked involving such numbers, the rules of exponents are applied to the operations involving powers of ten.



a. To multiply powers of ten, add exponents,

$$10^3 \times 10^2 = 1000 \times 100 = 100,000 = 10^{(3+2)} = 10^5$$

$$10^2 \times 10^6 \times 10^3 = 10^{(2+6+3)} = 10^{11}$$

$$10^{10} \times 10^{-4} = 10^{(10-4)} = 10^6$$

b. To divide powers of ten, subtract the exponents of the denominator from the exponents of the numerator.

$$\frac{10^5}{10^3} = \frac{100,000}{1000} = 100 = 10^{(5-3)} = 10^2$$

$$\frac{10^4}{10^6} = \frac{10,000}{1,000,000} = 10^{(4-6)} = 10^{-2}$$

$$\frac{10^8}{10^{-10}} = \frac{100,000,000}{\frac{1}{10,000,000,000}} = 10^{[8-(-10)]} = 10^{18}$$

c. To raise a power of ten to a power, multiply the exponent by the power to which it is being raised.

$$(10^3)^2 = 10^3 \times 10^3 = 10^{3 \times 2} = 10^6$$

$$(10^6)^{\frac{1}{2}} = \sqrt{10^6} = 10^{6 \times \frac{1}{2}} = 10^3$$

Examples:

$$a. (3 \times 10^{10}) \times (2 \times 10^{10}) = (3 \times 2) (10^{10}) (10^{10}) = 6 \times 10^{20}$$

$$b. (1.5 \times 10^{-12}) \times (2.0 \times 10^{25}) = 3.0 \times 10^{13}$$

$$c. \frac{3.0 \times 10^{10}}{1.5 \times 10^5} = 2.0 \times 10^5$$

$$d. \frac{9.0 \times 10^{-27}}{3.0 \times 10^{-20}} = 3.0 \times 10^{-7}$$

$$e. (3.0 \times 10^{10})^2 = (3.0)^2 \times (10^{10})^2 = 9.0 \times 10^{20}$$

$$f. (2.5 \times 10^{-15})^2 = (2.5)^2 \times (10^{-15})^2 = 6.25 \times 10^{-30}$$

## PROBLEMS

More to practice on. Answers will be found again on Page 289.

$$1. \quad \frac{(0.048 \times 10^{-8}) (60,000 \times 10^{19}) (1,000,000)}{(4,800,000) (6.0 \times 10^{23})}$$

$$2. \quad \frac{(4.8 \times 10^{-10}) (2) (4.8 \times 10^{-10})}{(1 \times 10^{-12})^2}$$

$$3. \quad \frac{(2) (3.1416)^2 (9 \times 10^{-28}) (4.8 \times 10^{-10})^4}{(3 \times 10^{10}) (6.6 \times 10^{-27})^3}$$

$$4. \quad \frac{(6 \times 10^{23} \times 4.8 \times 10^{-10})^2}{(1000 \times 100)^2}$$

$$5. \quad \frac{(3)^2 (6.6 \times 10^{-27})^2}{(4) (3.1416)^2 (4.8 \times 10^{-10})^2 (9 \times 10^{-28})}$$

## USE OF EXPONENTIAL TABLES

Many of the equations met in radiological safety will be exponential equations; that is, equations involving a term which is expressed in exponential form.

Examples of these are:

$$N = N_0 e^{-\lambda t} \quad \text{decay of radioactive isotope}$$

$$I = I_0 e^{-\mu x} \quad \text{decrease in intensity of a parallel beam of electromagnetic radiation due to absorption}$$

$$Q = Q_0 e^{-t/RC} \quad \text{decrease of charge on a condenser in an RC circuit}$$

$$I = I_0 e^{-\sigma nx} \quad \text{decrease in intensity of a parallel neutron beam due to absorption.}$$

Note that even though the symbols used vary from equation to equation, all of the equations are mathematically of the same form. Here we are not concerned with the physics of the various equations, but desire only to solve them when all of the quantities except one are given as known values.

### SOLUTIONS

Typical problems are worked below. The method of solution applies equally well to any equation of the type under discussion.

a. Given the equation:  $N = N_0 e^{-\lambda t}$

where:  $N_0 = 1.0 \times 10^{12}$  atoms

$\lambda = 0.0055 \text{ sec}^{-1}$

$t = 100 \text{ sec}$

Solve for N. Substituting given values in the equation,

$$N = 1.0 \times 10^{12} e^{(-0.0055)(100)}$$

$$N = 1.0 \times 10^{12} e^{-0.55}$$

Next, by consulting a table giving the value of e raised to various powers, it is found that,

$$e^{-0.55} = 0.577$$

$$\text{So: } N = 1.0 \times 10^{12} \times 0.577 = 5.77 \times 10^{11} \text{ atoms} \quad (\text{Answer})$$

b. Given the equation:  $I = I_0 e^{-\sigma n x}$   
 where:  $I_0 = 980 \text{ neutrons/cm}^2/\text{sec}$   
 $I = 300 \text{ neutrons/cm}^2/\text{sec}$   
 $\sigma = 6 \times 10^{-21} \text{ cm}^2/\text{nucleus}$   
 $n = 5 \times 10^{18} \text{ nuclei/cm}^3$

Solve for x. Substituting values in the equation,

$$300 = 980 e^{-0.03x}$$

$$\frac{300}{980} = 0.306 = e^{-0.03x} \quad (a)$$

Next, consult a table of e raised to various powers to find to what power e must be raised to obtain a result of 0.306. It is found from the table that:

$$e^{-1.18} = 0.306$$

Since from equation (a) above,

$$e^{-0.03x} = 0.306$$

we have the two equalities,

$$e^{-0.03x} = 0.306$$

and

$$e^{-1.18} = 0.306$$

Since these equalities are true, we can write:

$$-0.03x = -1.18$$

and

$$x = \frac{1.18}{.03}$$

$$x = 39.3 \text{ cm} \quad (\text{Answer})$$

## PROBLEMS

Practice on the problems below and check your answers. Answers will be found on the following page.

1. If  $A = A_0 e^x$ , and  $A_0 = 10$ , and  $x = 2$ , what is value of  $A$ ?
2. If  $I = I_0 e^{-bx}$ , and  $b = 2$ , and  $x = 1.5$ , what is the ratio of  $I_0/I$ ?
3. If  $A = A_0 e^{-\lambda t}$ , and  $A = 0.1$ ,  $A_0 = 100$ ,  $\lambda = 0.021 \text{ min}^{-1}$ ; solve for  $t$ .
4. If  $A = A_0 e^{-\lambda t}$ , and  $A = 50 \times 10^{-6}$ ,  $\lambda = 0.021 \text{ min}^{-1}$ ,  $t = 329 \text{ min}$ ; solve for  $A_0$ .
5. If  $N = N_0 e^{-\lambda t}$ , and  $N_0 = 10$ ,  $\lambda = 0.181 \text{ days}^{-1}$ ,  $t = 10 \text{ days}$  solve for  $N$ .

## ANSWERS TO PROBLEMS REFERENCED IN APPENDIX C

Problem on Page 282:

1.  $m = 5$

2.  $x = 2.5$

3.  $s = 3.5$

4.  $w = 13$

5.  $s = 1 \frac{12}{43}$

Problem on Page 285:

1.  $1.0 \times 10^{-10}$

2.  $4.61 \times 10^5$

3.  $1.2 \times 10^5$

4.  $9.0 \times 10^{18}$

5.  $5.0 \times 10^{-8}$

Problem on Page 288:

1.  $A = 73.9$

2.  $\frac{I_o}{I} = 20.1$

3.  $t = 329$

4.  $A_o = 5 \times 10^{-2}$

5.  $N = 1.64$

**( P O R A C C )**

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## APPENDIX D

### CONVERSION FACTORS

| <u>Multiply</u>                          | <u>By</u>                                                         | <u>To Obtain</u>                                                                                             |
|------------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
| Centimeters (cm)                         | 10<br>.3937<br>$3.28 \times 10^{-2}$                              | Millimeters (mm)<br>Inches (in.)<br>Feet (ft)                                                                |
| Cubic centimeters (cc)(cm <sup>3</sup> ) | 1<br>$6.102 \times 10^{-2}$<br>$2.642 \times 10^{-4}$             | Milliliters (ml)<br>Cubic inches (in. <sup>3</sup> )<br>Gallons (gal)                                        |
| Cubic feet (cu ft) (ft <sup>3</sup> )    | 28.317<br>7.481<br>$2.831 \times 10^{-2}$                         | Liters (l)<br>Gallons (gal)<br>Cubic meters (m <sup>3</sup> )                                                |
| Cubic meters (cu m) (m <sup>3</sup> )    | 35.31<br>$2.642 \times 10^2$                                      | Cubic feet (cu ft)<br>Gallons (gal)                                                                          |
| Curies (c)                               | $10^3$<br>$10^6$<br>$3.7 \times 10^{10}$<br>$2.22 \times 10^{12}$ | Millicuries (mc)<br>Microcuries (μc)<br>Disintegrations per second (d/s)<br>Disintegrations per minute (d/m) |
| Inches (in.)                             | 2.54                                                              | Centimeters (cm)                                                                                             |
| Kilograms (kg)                           | 2.204                                                             | Pounds (lb)                                                                                                  |
| Liters (l)                               | $10^3$<br>33.8147<br>1.0567                                       | Cubic centimeters (cc)<br>Fluid ounces (fl oz)<br>Quarts (qt)                                                |
| Meters (m)                               | 39.37<br>3.28                                                     | Inches (in.)<br>Feet (ft)                                                                                    |
| Microcuries (μc)                         | $3.7 \times 10^4$<br>$2.22 \times 10^6$                           | Disintegrations per second (d/s)<br>Disintegrations per minute (d/m)                                         |
| Microns (μ)                              | $10^{-6}$<br>$10^{-4}$                                            | Meters (m)<br>Centimeters (cm)                                                                               |
| Mils                                     | $10^{-3}$                                                         | Inches (in.)                                                                                                 |



| <u>Multiply</u>                                                     | <u>By</u>                                       | <u>To Obtain</u>                                                                                                                                                    |
|---------------------------------------------------------------------|-------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ounces (oz)                                                         | 28.35                                           | Grams (gm)                                                                                                                                                          |
| Pounds (lb)                                                         | 16<br>453.592                                   | Ounces (oz)<br>Grams (gm)                                                                                                                                           |
| Rads(units of absorbed dose<br>of ionizing radiation)               | 1.00                                            | Ergs per gram of irra-<br>diated material<br>(erg/gm)                                                                                                               |
| Roentgens (r) (under standard<br>conditions: 0°C and<br>760 mm Hg)  | 87<br>$6.77 \times 10^4$<br>$2.083 \times 10^9$ | Ergs per gram of air<br>(erg/gm)<br>Million electron volts<br>per cubic centimeter<br>of air (Mev/cc)<br>Ion pairs per cubic<br>centimeter of air<br>(ion pairs/cc) |
| Roentgens equivalent<br>physical (rep)                              | 93                                              | Ergs per gram of<br>tissue (erg/gm)                                                                                                                                 |
| Square centimeters (cm <sup>2</sup> )                               | 0.155<br>$1.076 \times 10^{-3}$                 | Square inches (in. <sup>2</sup> )<br>Square feet (sq ft)(ft <sup>2</sup> )                                                                                          |
| Square feet (ft <sup>2</sup> )                                      | 929.03<br>144                                   | Square centimeters (cm <sup>2</sup> )<br>Square inches (in. <sup>2</sup> )                                                                                          |
| Square inches (in. <sup>2</sup> )                                   | 6.45163                                         | Square centimeters (cm <sup>2</sup> )                                                                                                                               |
| Square meters (m <sup>2</sup> )                                     | 10.76                                           | Square feet (ft <sup>2</sup> )                                                                                                                                      |
| Density in milligrams per<br>cubic centimeter (mg/cm <sup>3</sup> ) | Thickness in cm                                 | Milligrams per sq cm<br>(mg/cm <sup>2</sup> )                                                                                                                       |

## APPENDIX E

### GRAPHS AND TABLES FOR ESTIMATING DOSE, DOSE RATE AND SHIELDING THICKNESS.

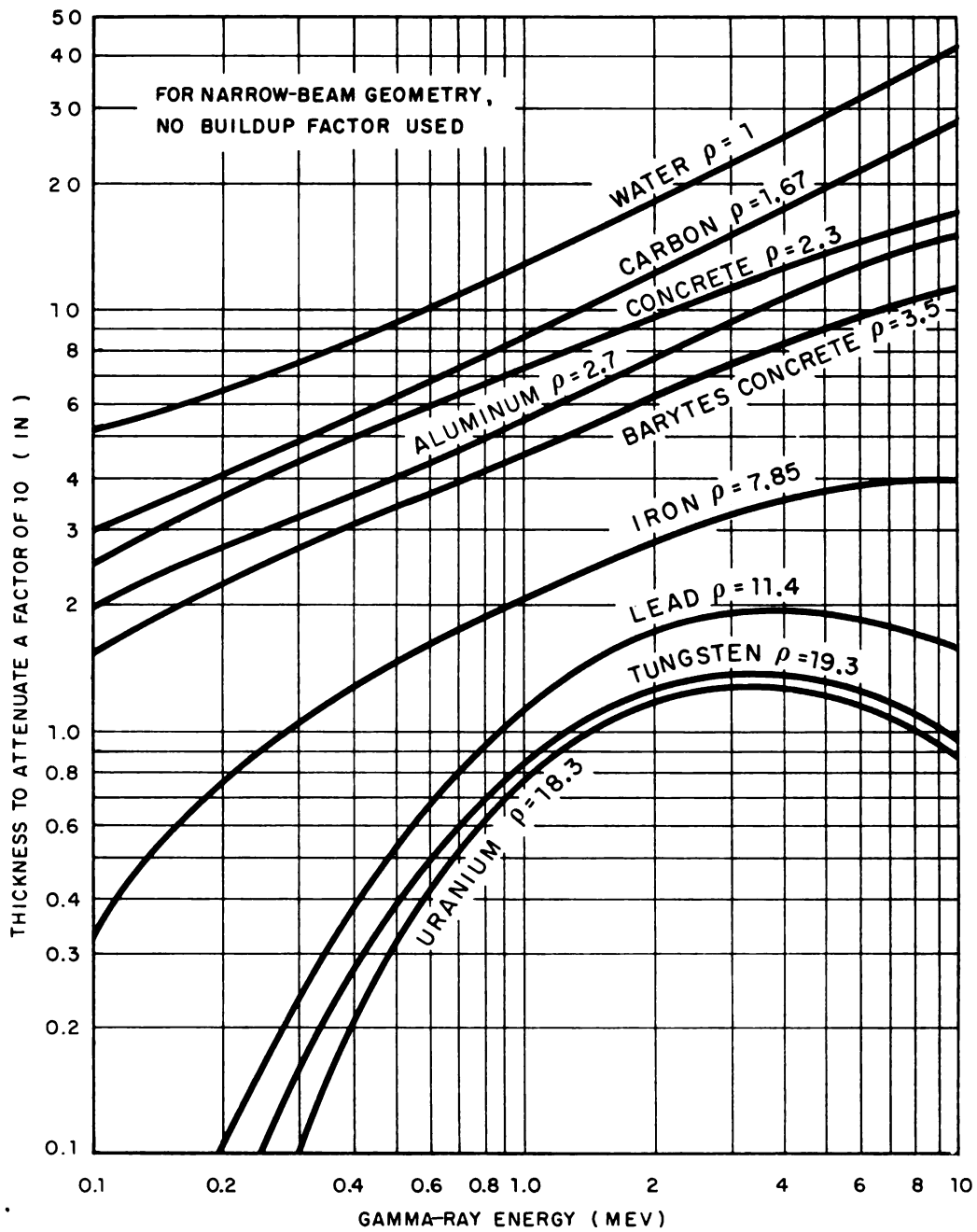


FIG. E-1. TENTH-VALUE THICKNESS FOR GAMMA-RAY ABSORPTION

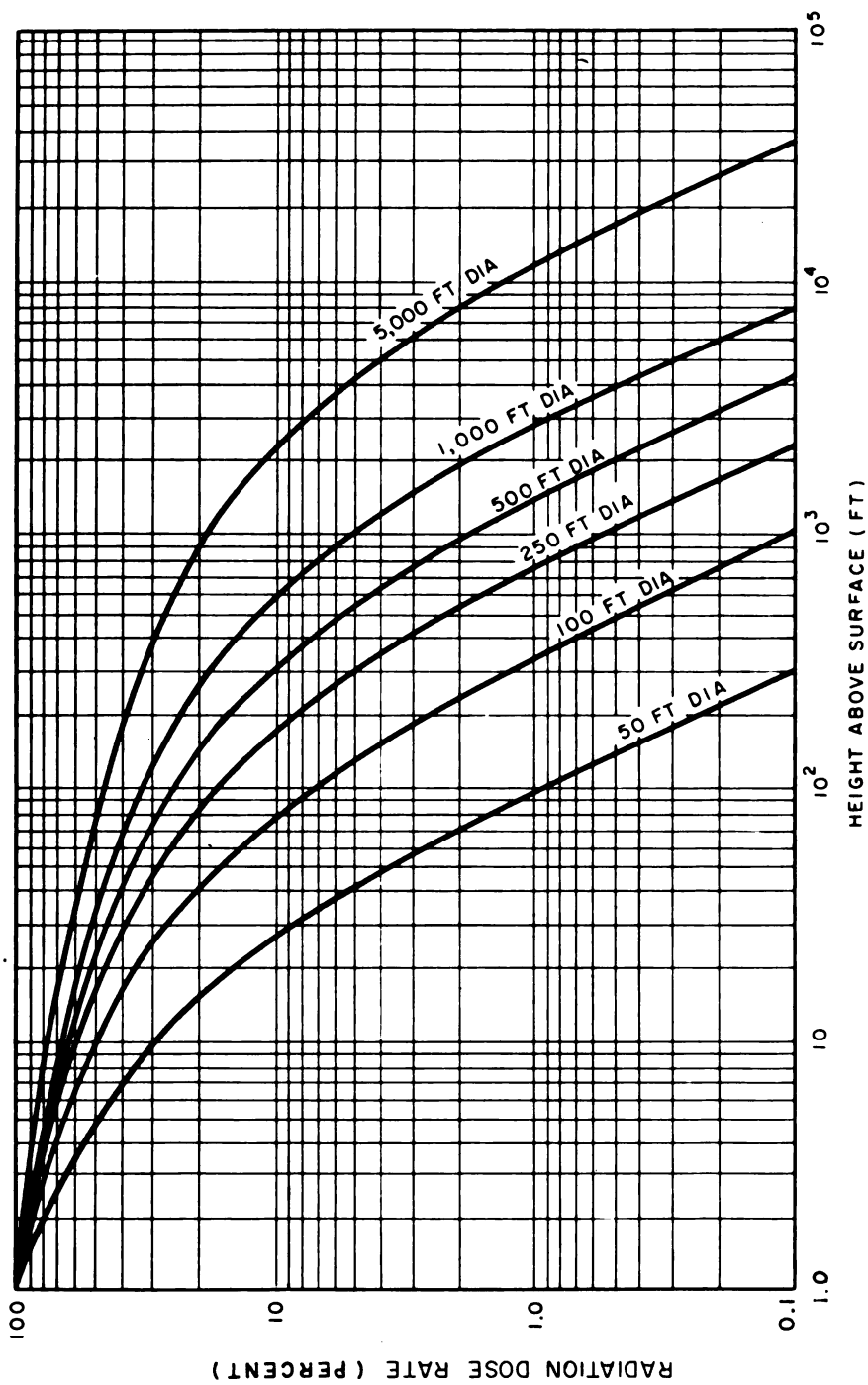


FIG. E-2. THEORETICAL RELATIVE RADIATION DOSE RATE VS. HEIGHTS FROM VARIOUS CIRCULAR FIELDS (NORMALIZED TO 100% DOSE RATE AT 1 FT)

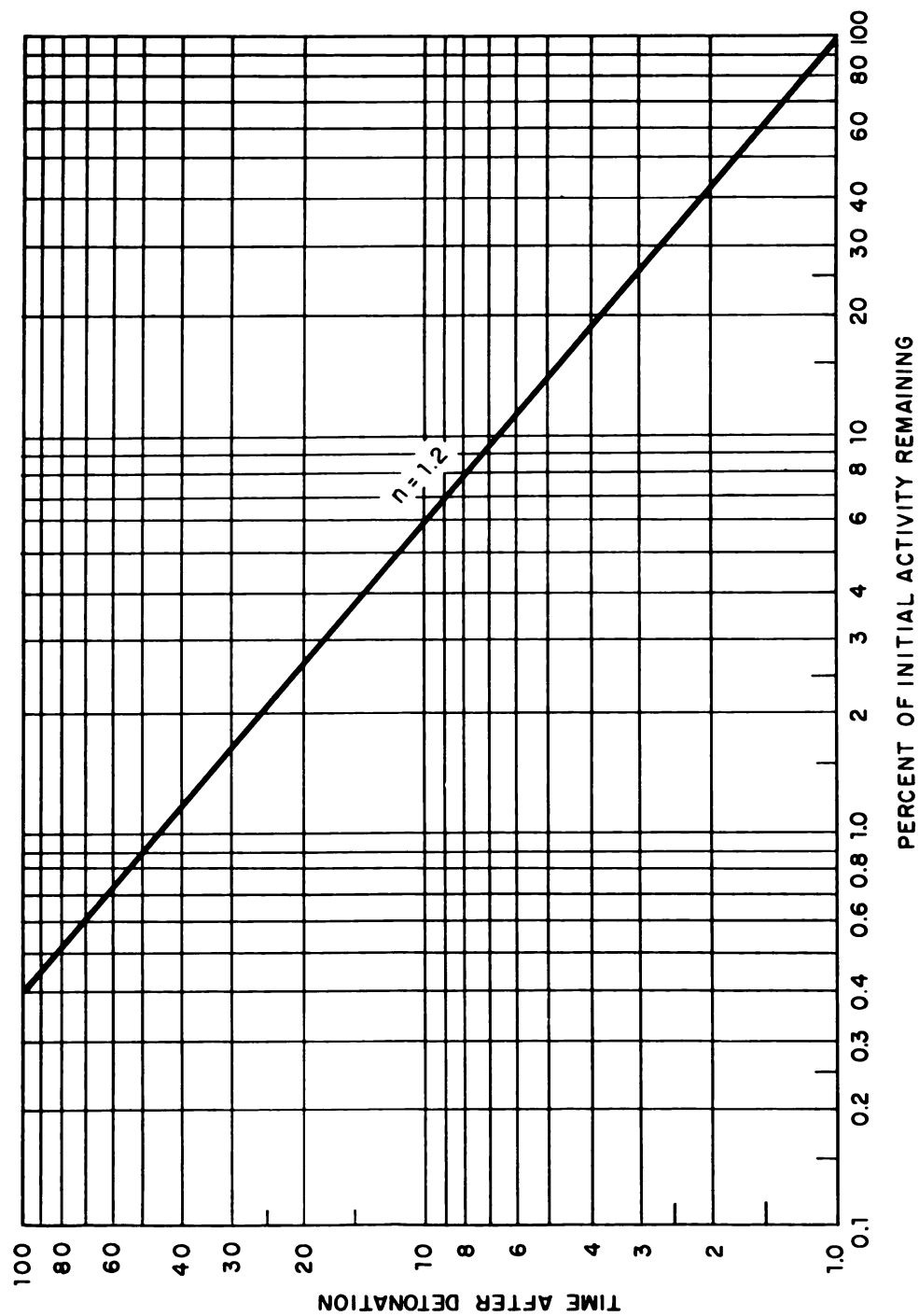


FIG. E-3.  $t^{-1.2}$  DECAY CURVE

TABLE E-1

CORRECTION OF R/HR AT ANY TIME TO 1 HOUR AFTER BURST

| Time After Burst | Factor | Time After Burst | Factor | Time After Burst | Factor |
|------------------|--------|------------------|--------|------------------|--------|
| 0:00             | -----  | 2:00             | 2.28   | 11:00            | 17.2   |
| 0:05             | .050   | 2:05             | 2.40   | 11:30            | 18.2   |
| 0:10             | .121   | 2:10             | 2.52   | 12:00            | 19.1   |
| 0:12             | .149   | 2:15             | 2.63   | 12:30            | 20.0   |
| 0:14             | .181   | 2:20             | 2.75   | 13:00            | 21.0   |
| 0:16             | .211   | 2:25             | 2.86   | 13:30            | 21.9   |
| 0:18             | .244   | 2:30             | 2.98   | 14:00            | 22.9   |
| 0:20             | .278   | 2:35             | 3.10   | 14:30            | 23.9   |
| 0:22             | .306   | 2:40             | 3.23   | 15:00            | 25.0   |
| 0:24             | .323   | 2:45             | 3.35   | 15:30            | 26.0   |
| 0:26             | .377   | 2:50             | 3.48   | 16:00            | 27.0   |
| 0:28             | .410   | 2:55             | 3.60   | 16:30            | 27.9   |
| 0:30             | .444   | 3:00             | 3.70   | 17:00            | 28.8   |
| 0:32             | .481   | 3:05             | 3.82   | 17:30            | 30.0   |
| 0:34             | .512   | 3:10             | 3.95   | 18:00            | 31.0   |
| 0:36             | .550   | 3:15             | 4.08   | 18:30            | 32.0   |
| 0:38             | .589   | 3:20             | 4.20   | 19:00            | 33.2   |
| 0:40             | .621   | 3:25             | 4.31   | 19:30            | 34.1   |
| 0:42             | .658   | 3:30             | 4.45   | 20:00            | 35.2   |
| 0:44             | .695   | 3:40             | 4.70   | 21:00            | 37.2   |
| 0:46             | .730   | 3:50             | 4.93   | 22:00            | 39.6   |
| 0:48             | .770   | 4:00             | 5.19   | 23:00            | 41.7   |
| 0:50             | .813   | 4:10             | 5.43   | 24:00            | 43.9   |
| 0:52             | .848   | 4:20             | 5.72   | 25:00            | 46.1   |
| 0:54             | .886   | 4:30             | 5.95   | 26:00            | 48.4   |
| 0:56             | .926   | 4:40             | 6.17   | 27:00            | 50.5   |
| 0:58             | .962   | 4:50             | 6.49   | 28:00            | 52.8   |
| 1:00             | 1.000  | 5:00             | 6.76   | 29:00            | 54.9   |
| 1:02             | 1.042  | 5:15             | 7.15   | 30:00            | 57.5   |
| 1:04             | 1.070  | 5:30             | 7.52   | 32:00            | 62.1   |
| 1:06             | 1.117  | 5:45             | 7.95   | 34:00            | 66.7   |
| 1:08             | 1.162  | 6:00             | 8.33   | 36:00            | 71.5   |
| 1:10             | 1.198  | 6:15             | 8.78   | 38:00            | 75.7   |
| 1:12             | 1.242  | 6:30             | 9.18   | 40:00            | 80.6   |
| 1:14             | 1.290  | 6:45             | 9.62   | 42:00            | 85.0   |
| 1:16             | 1.325  | 7:00             | 10.00  | 44:00            | 90.0   |
| 1:18             | 1.360  | 7:15             | 10.42  | 46:00            | 94.3   |
| 1:20             | 1.409  | 7:30             | 10.88  | 48:00            | 100.0  |
| 1:22             | 1.450  | 7:45             | 11.3   | 50:00            | 106.3  |
| 1:24             | 1.493  | 8:00             | 11.8   | 55:00            | 117    |
| 1:26             | 1.537  | 8:30             | 12.7   | 60:00            | 130    |
| 1:28             | 1.588  | 8:45             | 13.1   | 65:00            | 142    |
| 1:30             | 1.621  | 9:00             | 13.5   | 70:00            | 155    |
| 1:35             | 1.740  | 9:15             | 14.0   | 72:00            | 160    |
| 1:40             | 1.852  | 9:30             | 14.5   | 100:00           | 238    |
| 1:45             | 1.961  | 9:45             | 15.0   | 500:00           | 1850   |
| 1:50             | 2.06   | 10:00            | 15.4   |                  |        |
| 1:55             | 2.18   | 10:30            | 16.0   |                  |        |

## INSTRUCTIONS AND SAMPLE CALCULATION FOR TABLE E-1

(1) From observed radiation level at a given time compute the radiation dose rate at 1 hour after the burst.

Solution: Look up the factor corresponding to the time of the original reading. Multiply this reading by the factor.

SAMPLE: At 1 hour and 55 minutes after the burst a reading of 31 r/hr was observed. The factor corresponding to 1 hour and 55 minutes (1:55) is 2.18. The observed reading is multiplied by this factor, i. e. ,  
 $31 \times 2.18 = 67.6 \text{ r/hr at 1 hour.}$

(2) From known dose rate at 1 hour after the burst compute it at any other time (less frequently done).

Solution: Look up the factor corresponding to the time desired and divide it into the rate at 1 hour.

TABLE E-2  
FISSION-PRODUCT ACCUMULATED DOSE TABLE

| Time<br>After<br>Burst | Roentgens per hour at 1 hour after burst |      |      |       |       |     |     |     |     |     |     |     |     |     |       |       |
|------------------------|------------------------------------------|------|------|-------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|-------|
|                        | 1                                        | 5    | 10   | 15    | 20    | 25  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 | 150   | 200   |
| 0:00                   | 1.40                                     | 7.0  | 14.0 | 21.0  | 28.0  | 35  | 42  | 56  | 70  | 84  | 98  | 112 | 126 | 140 | 210   | 280   |
| 0:02                   | 2.25                                     | 12.5 | 22.0 | 34.5  | 44.0  | 57  | 66  | 88  | 125 | 132 | 154 | 176 | 213 | 220 | 345   | 440   |
| 0:03                   | 2.80                                     | 14.0 | 28.0 | 42.0  | 56.0  | 70  | 84  | 112 | 140 | 168 | 196 | 224 | 252 | 280 | 420   | 560   |
| 0:04                   | 3.15                                     | 15.8 | 31.5 | 47.3  | 63.0  | 89  | 104 | 146 | 158 | 208 | 250 | 292 | 304 | 315 | 470   | 630   |
| 0:05                   | 3.90                                     | 19.5 | 39.0 | 58.5  | 78.0  | 98  | 117 | 156 | 195 | 234 | 273 | 312 | 351 | 390 | 585   | 780   |
| 0:08                   | 4.20                                     | 21.0 | 42.0 | 63.0  | 84.0  | 105 | 126 | 168 | 210 | 252 | 294 | 336 | 378 | 420 | 630   | 840   |
| 0:10                   | 4.45                                     | 22.3 | 44.5 | 66.8  | 89.0  | 111 | 134 | 178 | 223 | 268 | 312 | 356 | 401 | 445 | 668   | 890   |
| 0:14                   | 4.67                                     | 23.4 | 46.7 | 70.1  | 93.4  | 117 | 140 | 187 | 234 | 280 | 327 | 374 | 421 | 467 | 701   | 934   |
| 0:16                   | 4.85                                     | 24.3 | 48.5 | 72.8  | 97.0  | 121 | 146 | 197 | 243 | 292 | 340 | 388 | 437 | 485 | 728   | 970   |
| 0:18                   | 5.00                                     | 25.0 | 50.0 | 75.0  | 100.0 | 125 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 | 750   | 1,000 |
| 0:20                   | 5.15                                     | 25.8 | 51.5 | 77.3  | 103.0 | 129 | 155 | 206 | 258 | 310 | 361 | 412 | 464 | 515 | 773   | 1,030 |
| 0:22                   | 5.23                                     | 26.2 | 52.3 | 78.5  | 105.0 | 131 | 157 | 210 | 262 | 314 | 367 | 420 | 472 | 523 | 785   | 1,050 |
| 0:24                   | 5.35                                     | 26.8 | 53.5 | 80.3  | 107.0 | 134 | 160 | 214 | 268 | 320 | 374 | 428 | 482 | 535 | 803   | 1,070 |
| 0:26                   | 5.43                                     | 27.2 | 54.3 | 81.5  | 109.0 | 136 | 163 | 218 | 272 | 326 | 381 | 436 | 490 | 543 | 815   | 1,090 |
| 0:28                   | 5.53                                     | 27.7 | 55.3 | 83.0  | 111.0 | 139 | 166 | 222 | 277 | 332 | 388 | 444 | 499 | 553 | 830   | 1,110 |
| 0:30                   | 5.60                                     | 28.0 | 56.0 | 84.0  | 112.0 | 140 | 168 | 224 | 280 | 336 | 392 | 448 | 504 | 560 | 840   | 1,120 |
| 0:35                   | 5.75                                     | 28.8 | 57.5 | 86.3  | 115.0 | 144 | 173 | 230 | 288 | 346 | 403 | 460 | 518 | 575 | 863   | 1,150 |
| 0:40                   | 5.90                                     | 29.5 | 59.0 | 88.5  | 118.0 | 148 | 177 | 236 | 295 | 354 | 413 | 472 | 531 | 590 | 885   | 1,180 |
| 0:45                   | 6.03                                     | 30.2 | 60.3 | 90.5  | 121.0 | 151 | 181 | 242 | 305 | 362 | 423 | 484 | 544 | 603 | 905   | 1,210 |
| 0:50                   | 6.13                                     | 30.7 | 61.3 | 92.0  | 123.0 | 154 | 184 | 246 | 307 | 368 | 430 | 492 | 553 | 613 | 920   | 1,230 |
| 0:55                   | 6.23                                     | 31.2 | 62.3 | 93.5  | 125.0 | 156 | 187 | 250 | 312 | 374 | 437 | 500 | 562 | 623 | 935   | 1,250 |
| 1:00                   | 6.30                                     | 31.5 | 63.0 | 94.5  | 126.0 | 158 | 189 | 252 | 315 | 378 | 441 | 504 | 567 | 630 | 945   | 1,260 |
| 1:05                   | 6.40                                     | 32.0 | 64.0 | 96.0  | 128.0 | 160 | 192 | 256 | 320 | 384 | 448 | 512 | 576 | 640 | 960   | 1,280 |
| 1:10                   | 6.50                                     | 32.5 | 65.0 | 97.5  | 130.0 | 163 | 195 | 260 | 325 | 390 | 455 | 520 | 585 | 650 | 975   | 1,300 |
| 1:20                   | 6.63                                     | 33.2 | 66.3 | 99.5  | 133.0 | 166 | 199 | 266 | 332 | 398 | 465 | 532 | 598 | 663 | 995   | 1,330 |
| 1:30                   | 6.73                                     | 33.7 | 67.3 | 101.0 | 135.0 | 169 | 202 | 270 | 337 | 404 | 472 | 540 | 607 | 673 | 1,010 | 1,350 |
| 1:40                   | 6.83                                     | 34.2 | 68.3 | 103.0 | 137.0 | 171 | 205 | 274 | 342 | 410 | 479 | 548 | 616 | 683 | 1,030 | 1,370 |
| 1:50                   | 6.92                                     | 34.6 | 69.2 | 104.0 | 138.0 | 173 | 207 | 276 | 346 | 414 | 483 | 552 | 622 | 692 | 1,040 | 1,380 |
| 2:00                   | 7.00                                     | 35.0 | 70.0 | 105.0 | 140.0 | 175 | 210 | 280 | 350 | 420 | 490 | 560 | 630 | 700 | 1,050 | 1,400 |
| 2:15                   | 7.10                                     | 35.5 | 71.0 | 106.0 | 142.0 | 178 | 212 | 284 | 355 | 424 | 496 | 568 | 639 | 710 | 1,060 | 1,420 |
| 2:30                   | 7.20                                     | 36.0 | 72.0 | 108.0 | 144.0 | 180 | 216 | 288 | 360 | 432 | 504 | 576 | 648 | 720 | 1,080 | 1,440 |
| 2:45                   | 7.26                                     | 36.3 | 72.6 | 109.0 | 145.0 | 181 | 218 | 290 | 363 | 436 | 508 | 580 | 653 | 726 | 1,090 | 1,450 |

TABLE E-2 (Cont'd)

| Time<br>After<br>Burst | Roentgens per hour at 1 hour after burst |      |       |       |       |     |     |     |     |     |     |     |       |       |       |       |
|------------------------|------------------------------------------|------|-------|-------|-------|-----|-----|-----|-----|-----|-----|-----|-------|-------|-------|-------|
|                        | 1                                        | 5    | 10    | 15    | 20    | 25  | 30  | 40  | 50  | 60  | 70  | 80  | 90    | 100   | 150   | 200   |
| 3:00                   | 7.33                                     | 36.7 | 73.3  | 110.0 | 147.0 | 184 | 220 | 294 | 367 | 440 | 514 | 588 | 661   | 733   | 1,110 | 1,470 |
| 3:30                   | 7.43                                     | 37.2 | 74.3  | 112.0 | 149.0 | 186 | 223 | 298 | 372 | 446 | 521 | 596 | 670   | 743   | 1,120 | 1,490 |
| 4:00                   | 7.55                                     | 37.8 | 75.5  | 113.0 | 151.0 | 189 | 226 | 302 | 378 | 452 | 528 | 604 | 680   | 755   | 1,130 | 1,510 |
| 4:30                   | 7.65                                     | 38.3 | 76.5  | 115.0 | 153.0 | 191 | 230 | 306 | 383 | 460 | 536 | 612 | 689   | 765   | 1,150 | 1,530 |
| 5:00                   | 7.75                                     | 38.8 | 77.5  | 116.0 | 155.0 | 194 | 232 | 310 | 388 | 464 | 542 | 620 | 698   | 775   | 1,160 | 1,550 |
| 6:00                   | 7.87                                     | 39.9 | 78.7  | 119.0 | 157.0 | 197 | 238 | 314 | 399 | 476 | 552 | 628 | 713   | 787   | 1,190 | 1,570 |
| 7:00                   | 7.97                                     | 40.0 | 79.7  | 120.0 | 160.0 | 200 | 240 | 320 | 400 | 480 | 560 | 640 | 720   | 797   | 1,200 | 1,600 |
| 8:00                   | 8.06                                     | 40.3 | 80.6  | 121.0 | 161.0 | 201 | 242 | 322 | 403 | 484 | 564 | 644 | 725   | 806   | 1,210 | 1,610 |
| 9:00                   | 8.15                                     | 40.8 | 81.5  | 122.0 | 163.0 | 204 | 244 | 326 | 408 | 488 | 570 | 652 | 734   | 815   | 1,220 | 1,630 |
| 10:00                  | 8.20                                     | 41.0 | 82.0  | 123.0 | 164.0 | 205 | 246 | 328 | 410 | 492 | 574 | 656 | 738   | 820   | 1,230 | 1,640 |
| 13:00                  | 8.40                                     | 42.0 | 84.0  | 126.0 | 168.0 | 210 | 252 | 336 | 420 | 504 | 588 | 672 | 756   | 840   | 1,260 | 1,680 |
| 17:00                  | 8.52                                     | 42.6 | 85.2  | 128.0 | 170.0 | 213 | 256 | 340 | 426 | 512 | 596 | 680 | 766   | 852   | 1,280 | 1,700 |
| 20:00                  | 8.62                                     | 43.1 | 86.2  | 129.0 | 172.0 | 215 | 258 | 344 | 431 | 516 | 602 | 688 | 775   | 862   | 1,290 | 1,720 |
| 24:00                  | 8.72                                     | 43.6 | 87.2  | 131.0 | 174.0 | 218 | 262 | 348 | 436 | 524 | 610 | 696 | 784   | 872   | 1,310 | 1,740 |
| 30:00                  | 8.83                                     | 44.2 | 88.3  | 133.0 | 177.0 | 221 | 266 | 354 | 442 | 532 | 620 | 708 | 796   | 883   | 1,330 | 1,770 |
| 40:00                  | 9.00                                     | 45.0 | 90.0  | 135.0 | 180.0 | 225 | 270 | 360 | 450 | 540 | 630 | 720 | 810   | 900   | 1,350 | 1,800 |
| 48:00                  | 9.07                                     | 45.4 | 90.7  | 136.0 | 181.0 | 227 | 272 | 362 | 454 | 544 | 634 | 724 | 816   | 907   | 1,360 | 1,810 |
| 60:00                  | 9.17                                     | 45.9 | 91.7  | 138.0 | 183.0 | 229 | 276 | 366 | 459 | 552 | 642 | 732 | 825   | 917   | 1,380 | 1,830 |
| 72:00                  | 9.25                                     | 46.3 | 92.5  | 139.0 | 185.0 | 231 | 278 | 370 | 463 | 556 | 648 | 740 | 833   | 925   | 1,390 | 1,850 |
| 100:00                 | 9.37                                     | 46.9 | 93.7  | 141.0 | 187.0 | 234 | 282 | 374 | 469 | 564 | 656 | 748 | 843   | 937   | 1,410 | 1,870 |
| 500:00                 | 9.83                                     | 49.2 | 98.3  | 148.0 | 189.0 | 246 | 296 | 378 | 492 | 592 | 674 | 756 | 870   | 983   | 1,480 | 1,890 |
| 1,000:00               | 10.00                                    | 50.0 | 100.0 | 150.0 | 200.0 | 250 | 300 | 400 | 500 | 600 | 700 | 800 | 900   | 1,000 | 1,500 | 2,000 |
| ∞                      | 11.35                                    | 57.0 | 114.0 | 171.0 | 228.0 | 285 | 342 | 456 | 570 | 684 | 798 | 912 | 1,036 | 1,140 | 1,710 | 2,280 |

## INSTRUCTIONS AND SAMPLE CALCULATIONS FOR TABLE E-2

Column 1 gives the time after the burst in hours and minutes. The headings at the top of the other columns are the dose rates at 1 hour after the burst. The entries in the body of the table give the total accumulated dose from the instant of the explosion up to the given time. Proper use of Table E-2 is best illustrated by sample problems.

**PROBLEM:** What radiation dose has been accumulated by a person who has been present at a given point since the bomb went off 2½ hours earlier? The dose rate at 1 hour after the burst was 25 r/hr.

**SOLUTION:** Refer to column headed 25. Entries give total accumulated dose at given times: at 8 minutes, 98 roentgens; at 30 minutes, 140 roentgens; and at 2 hours and 30 minutes, 180 roentgens.

**PROBLEM:** What radiation dose would be received by a person who came to this given point 2½ hours after the burst and stayed until 10 hours after the burst?

**SOLUTION:** This would be merely the difference between the dose at 10 hours and at 2½ hours, or (referring to column 25) 205 r - 180 r = 25 r.



**( P O R A C C )**

# **APPENDIX F**

## **MEASURES FOR RADIOLOGICAL ACCIDENTS**

The term "Radiological Accident" is applied to any accident involving the accidental release, escape, or spill of radioactive materials in such an amount that a health hazard exists or there is danger of spreading such contamination to clean areas.

Despite all safety precautions accidents will occur and standard procedures for dealing with accidents are an essential part of any radiological safety plan. Detailed procedures depend on the particular type of accident. The following are the emergency procedures suggested for radiological accidents in general:

- I. MINOR SPILLS INVOLVING NO RADIATION HAZARD TO PERSONNEL:
  - A. Notify all other persons in the area at once.
  - B. Admit into the area only those personnel necessary to deal with the spill.
  - C. Confine the spill immediately.
    1. Liquid spills:
      - a. Don protective gloves.
      - b. Place absorbent paper over spill.
    2. Dry spills:
      - a. Don protective gloves.
      - b. Dampen area thoroughly. Do not allow contamination to be spread or become an inhalation hazard.
  - D. Notify the Radiological Safety Officer (Health Physicist) as soon as possible.
  - E. Monitor all personnel involved in the spill and perform radiological survey of the spill area. (See Chapter 3.)
  - F. Decontaminate area, following safe practices for decontamination operations. (See Chapter 2.)
  - G. Monitor area for final clearance. (See Chapter 4.)
  - H. Take necessary corrective action to prevent future occurrences and prepare complete history of the incident for records.

**II. MAJOR SPILLS INVOLVING RADIATION HAZARD TO PERSONNEL:**

- A. Notify all personnel not involved in the spill to vacate the room at once.
- B. Vacate the room.
- C. Take immediate steps to decontaminate personnel involved, as necessary. (See Chapter 2.)
  - 1. If the spill is on the skin, flush thoroughly with water. Treat the washing materials as radioactive waste.
  - 2. If the spill is on clothing, discard outer or protective clothing at once.
- D. Notify the Radiological Safety Officer (Health Physicist) as soon as possible.
- E. Monitor all personnel involved in the spill and perform a radiological survey of the spill area. (See Chapter 3.)
- F. Decontaminate area, following safe practices for decontamination operations. (See Chapter 2.)
- G. Monitor area for final clearance. (See Chapter 4.)
- H. Take necessary corrective action to prevent future occurrences and prepare complete history of the incident for records.

**III. ACCIDENTS INVOLVING RADIOACTIVE DUSTS, MISTS, FUMES, ORGANIC VAPORS AND GASES:**

- A. Notify all other persons to vacate the room immediately.
- B. Hold breath and close escape valves, switch off air circulating devices, etc., if time permits.
- C. Vacate the room.
- D. Close all access doors and post guards to prevent re-entry to the room.
- E. Notify the Radiological Safety Officer at once.
- F. Report at once all known or suspected cases of inhalation of radioactive material to the Radiological Safety Officer.
- G. Monitor all personnel involved. (See Chapter 3.)
- H. Evaluate the hazard and take the necessary safety procedures for safe re-entry.
- I. Determine the cause of contamination and rectify the condition.
- J. Decontaminate the area. (See Chapter 2.)
- K. Perform air and monitoring surveys of the area before permitting work to be resumed. (See Chapter 3.)
- L. Prepare a complete history of the accident for record purposes.

**IV. INJURIES TO PERSONNEL INVOLVING RADIOLOGICAL CONTAMINATION:**

- A. Wash minor wounds immediately under running water.**
- B. Report all radiological accidents of personnel (wounds, overexposure, ingestion, inhalation) to the Radiological Safety Officer (Health Physicist) as soon as possible.**
- C. Call a physician qualified to treat radiation injuries at once.**
- D. Permit no person involved in a radiation injury to return to work without the approval of the attendant physician.**
- E. Prepare a complete history of the accident for Laboratory records.**

**V. FIRE OR OTHER MAJOR EMERGENCIES:**

- A. Notify all persons in the room, building or area at once.**
- B. Notify the fire department and other local safety personnel.**
- C. Attempt to put out fire if radiation hazard is not immediately present.**
- D. Notify the Radiological Safety Officer (Health Physicist).**
- E. Govern fire fighting or other emergency activities by restrictions imposed by the Radiological Safety Officer.**
- F. Following the emergency, monitor area and determine the decontamination measures needed. (See Chapters 2 and 3.)**
- G. Monitor all personnel involved in the emergency. (See Chapter 3.)**
- H. Decontaminate as required. (See Chapter 2.)**
- I. Monitor area before work is resumed. (See Chapter 3.)**
- J. Prepare a complete history of the emergency for record purposes.**

**VI. PERSONNEL RECORDS**

**All personnel involved in a radiological incident should have sufficient urine analysis and monitoring information entered into their health records to document exposure and contamination levels. (See Chapter 3.)**

**( P O R A C C )**

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# APPENDIX G

## RADIOLOGICAL SAMPLE ANALYSIS

This appendix is composed of three separate but related parts: COUNTING PROCEDURES, AEROSOL SAMPLING AND ANALYSIS, AND WATER SAMPLING AND ANALYSIS. The latter two parts are included in this Appendix since a final accurate evaluation of the information collected cannot be accomplished without making use of the counting procedure section.

The information included in each part is listed below:

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## **APPENDIX G-1**

### **COUNTING PROCEDURES**

#### **PURPOSE**

The purpose of counting any radioactive sample is to determine with a degree of accuracy the quantity and, often, the quality (type -  $\alpha\beta\gamma$  - and energy) of the radioactivity associated with the sample in question. The counting process may be carried to various degrees of precision. Counting procedures, as outlined in the appendix, should satisfy the general user who desires to evaluate an air sample, a water sample, or a wipe sample as a health hazard index. Those desiring greater accuracy should consult the appropriate texts on the subject, such as Experimental Nucleonics, by Bleuler, Goldsmith, Rinehart, or Nuclear Radiation Physics, by Lapp and Andrews.

#### **EQUIPMENT**

The equipment required for counting consists of a unit capable of detecting the radiations of interest (detector) and a unit (scaler) capable of recording the signals put out by the detector. The detector and scaler require an electrical supply of generally 110 or 220 volt AC 60 cycle single-phase. Sometimes a power-supply voltage-regulator and line-noise filter must be used to stabilize the input power. The detector and scaler should be placed in an area of low background radiation. and the detector, if beta and/or gamma sensitive, will require a local shield called a "counting pig."

#### **COUNTING ROOM PRACTICES**

Several rules for counting rooms follow:

1. No loose contamination or unshielded sources allowed. Such sources can raise the counting rate or background in the area.
2. Count only properly mounted samples.
3. Designate area as "Off Limits" to all personnel except the operators and repair technicians.
4. Never handle samples and standards with bare hands. Use tweezers or similar equipment.
5. Samples which will obviously contaminate the detector chamber should not be placed in the counter.
6. When not in use, all detector chambers should be kept in the closed position to prevent contamination entry.

## PROCEDURES

The following counting procedures are based on the assumption that the equipment is properly connected and in operating order. Since there are many varieties of detectors and scalers, a general procedure will be given for the simpler types. The manufacturer's instruction manual should be consulted for proper operation and maintenance of each type of equipment.

### A. Geiger-Mueller Detector

G-M tubes generally operate from 600 to 1500 volts supplied from the variable high-voltage supply of the scaler. The G-M tube must be operated on the proper portion of the plateau curve as shown in Figure G-1.

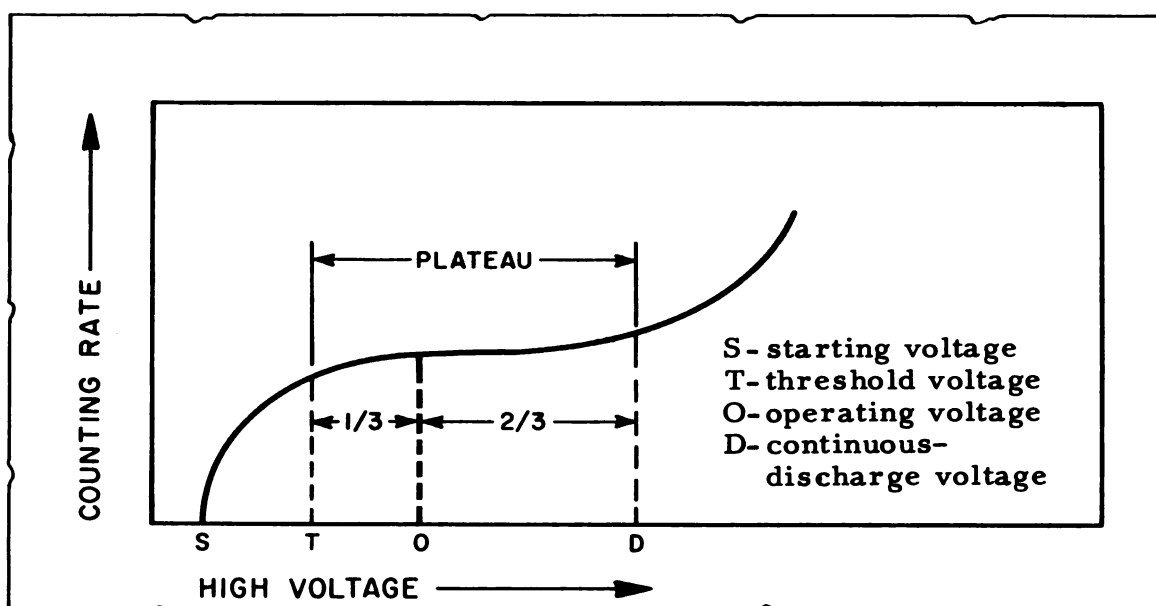


FIG. G-1 TYPICAL CHARACTERISTIC CURVE FOR G-M TUBES

Fig. G-1 indicates that the G-M tube will start to count at some voltage value above zero, S. This count rate will increase until the voltage is raised to the threshold value, T. The counting rate will be fairly constant as the voltage is raised from T to the continuous discharge point D. Raising the voltage value from point T to point D does not change the count rate appreciably. Above point D, the G-M tube goes into continuous discharge. The region of the curve from T to D is the plateau of the G-M tube. The G-M tube should be operated at point O, above T, one-third the distance along TD.



## **1. Determining G-M Plateau**

The plateau of a G-M tube may be determined by the following steps:

- a. Turn on the main power to the scaler and allow to warm up for at least 5 minutes. Be sure the high-voltage switch is off.
- b. Turn the high voltage adjustments to zero and turn on the high voltage power switch. Allow at least 15 minutes for warm-up and stabilization.
- c. Open the detector shield and place a beta or beta-gamma source in the counting position. This source should have an activity level between 1000 d/m and 30,000 d/m.
- d. Turn on the scaler count-switch. The scaler should be set for manual counting.
- e. Slowly raise the high voltage until the scaler begins to count pulses from the detector.
- f. Stop the counting and reset all lights and the register at zero.
- g. Record the high voltage value and count for at least a 2 minute counting interval. At the end of the counting time, record the counting rate (c/m) opposite the voltage.
- h. Repeat steps f and g after raising the high voltage by 25 or 50 volt increments. Repeat this procedure, raising the voltage each time, until there is sufficient data to plot a plateau. Never raise the high voltage to the continuous discharge voltage. Continuous discharge will damage the G-M tube.
- i. Plot the data obtained on linear graph paper to obtain a curve similar to that in Fig. G-1. The operating voltage is then set at a value corresponding to point 0 in Fig. G-1 (one-third the distance along the plateau).
- j. Generally, the G-M tube will operate at this point until the tube is no longer useful. Check the plateau about once each week during steady use or whenever a deviation of over 5% in counting efficiency is noted or after any repair or alteration to the scaler or the high voltage supply. Always determine the plateau for each counting tube; do not use the manufacturer's operating voltage stated on the G-M tube.

## **2. Determining Background**

All counting equipment has a background counting rate, due to cosmic and stray radiation penetrating the lead shield (counting pig), from radioactivity contained in the materials which make up the pig, G-M tube, and other components of the counter, and from contamination accumulated in the detection unit. The background counting rate is determined by removing all sources from the counting pig and taking at least a 10 minute count. The background counting rate should be checked periodically during the day or at least at the start and finish of the counting operation.

## **3. Determining Efficiency**

The efficiency of a counter is affected by many factors, such as geometry of the source, backscatter from material on which source is mounted, and characteristics of the detector (sensitive volume, window thickness, etc.). However, for simplicity, the efficiency may be regarded as the ratio of the number of counts observed to the number of disintegrations placed into the position for counting. In short, if a source that is known to decay at 1000 d/m is placed in the counter and only 200 c/m are measured by the equipment, the resultant efficiency is  $\frac{200}{1000} = 20\%$ . Thus, any source made of a similar material, mounting, etc., placed in the machine will show only 20% of full value on the scaler. To convert this count rate to disintegrations, the observed count rate minus background rate must be divided by the efficiency. The procedure is as follows:

- a. Determine the background with the scaler-detector unit at the proper operating high voltage.
- b. Place a known source (standard) in the unit and note the count rate. At least 10 minutes counting time or 10,000 counts are required.
- c. Divide the total count by the counting time to determine count rate. Subtract background count rate from the observed count rate.
- d. Divide the corrected count rate by the known d/m value of standard. This is the efficiency of the unit for that particular counting setup.
- e. Divide all sample counting rates by this efficiency to determine the disintegration or d/m value.
- f. AS ADDITIONAL GOOD PRACTICE, DETERMINE THE EFFICIENCY WITH A SOURCE SIMILAR IN D/M VALUE, ISOTOPE, AND SOURCE MOUNTING TO THE MATERIAL TO BE COUNTED.

- g. Determine the efficiency of the shelf (distance from the detector) to be used in counting. The higher the activity level of the sample, the further from the tube the shelf will have to be located. Extremely high activity samples may be counted by cutting them into sections.
- h. Do not attempt to operate a G-M counter at counting rates above 50,000 c/m.

## B. Scintillation Counters

A scintillation counting system consists of a scaling unit, high voltage supply, detector, and preamplifier. The detector is a crystal which is sensitive to radiation and which emits light when struck by radiation. The light so produced is detected and amplified by the photomultiplier tube to produce an electrical pulse. This pulse is again amplified to produce a signal or pulse on the scaler. A precision high voltage supply is usually required to provide the high voltage for the photomultiplier tube.

The crystal or scintillation material selected for a particular type of counter depends on the type of radiation to be detected. Silver activated zinc sulfide,  $\text{ZnS(Ag)}$ , crystals are used for alpha counting since they are efficient for alpha radiation but do not respond to beta or gamma radiation. Since  $\text{ZnS(Ag)}$  crystals absorb much of their own light, they are used in thin layers which consequently absorb little or no beta or gamma energy. Other materials such as anthracene, sodium iodide (NaI), naphthalene, trans-stilbene, etc., will transmit their own light and thus can be used as thick crystals. With a thick crystal, the beta and gamma energy can be absorbed to produce measurable light pulses.

Since the photomultiplier tube to be used is sensitive to light from any source, the tube and crystal are enclosed in a light-tight shield. One can generally tell the type of detector by noting the thickness of the crystal and the degree of shielding. An alpha scintillation counter requires no radiation shielding and has a thin crystal.

The scintillation counter has no plateau and operates at a voltage determined by the characteristics of the photomultiplier. The voltage is selected by noting the manufacturer's recommended range for the photomultiplier tube and then adjusting the applied voltage in this range to give a low background with reasonable counting efficiency.

Photomultipliers operate in the range of 900 to 1900 volts. Background counts are caused by stray radiations entering the scintillating media or by electron multiplication resulting from spurious electron emission inside the structure of the photo tube. The higher the voltage, the greater the electron multiplication.

The electron emissive surface (cathode) will emit electrons when light from the scintillating element is directed to it. Organic and inorganic scintillating materials are selected for the ultraviolet light produced by their interaction with ionizing radiation. The electron emissive surface is a thin coating of cesium-antimony oxide inside of the glass envelope of the photomultiplier tube. The electron multiplication through 10 stages is approximately  $10^6$ . A photomultiplier tube is extremely sensitive to light and will be damaged if exposed to visible light while the high voltage is on.

Some scintillation counting systems have an additional feature called a pulse height selector (phs) or discriminator which permits the operator to select the size of the pulse he desires to count. If the photon or particle is of fairly high energy, the discriminator or phs setting of the system may be adjusted to reduce background. In general, the phs and voltage value are adjusted to give about 25% efficiency with as low a background as possible. Once the pulse height selector is set, all pulses below the set value will be rejected and not registered. If the isotope being counted is replaced with one of low energy, the phs will have to be readjusted to allow the weaker pulses to be counted. IF POSSIBLE, DETERMINE THE EFFICIENCY OF THE SYSTEM BY USING THE SAME ISOTOPE, MOUNTING, AND SOURCE STRENGTH AS THE SAMPLES TO BE COUNTED. This will balance out many difficulties that an inexperienced person is not capable of solving.

To determine the efficiency of a scintillation counter, the sample is placed in front of the crystal and the light-tight housing closed. The efficiency of the system is determined by dividing the corrected count rate by the known d/m value of the sample source. Any unknown source of the same energy, mounting, etc., counted at the same distance from the detector can be corrected by the efficiency number to give its disintegrations per minute.

The two texts mentioned as references for this Appendix should be consulted for further information. (Page 306.)

### C. Other Types of Counters

Many other types of counters are used for nuclear radiation detecting and counting. The general operating principles are the same as those described for G-M and scintillation systems. For use of these systems it is recommended that the manufacturer's instruction book be consulted.

#### D. Sample Counting

The following procedures are recommended for sample counting:

1. Check to determine that all switches are in "off" position before plugging the unit into the power line.
2. Turn on power line. Allow at least a 5 minute warm-up time.
3. Turn high voltage adjustment switches to lowest value. Turn on high voltage, and allow a 2 minute warm up.
4. Adjust high voltage to proper operating value. Allow a minimum of 15 minutes for machine to stabilize, Page 308.
5. Take a 1 or 2 minute background check; note any excessive background from noise or contamination.
6. Insert standard and determine the counting rate by the method described under G-M Efficiency, Page 309.
7. Determine background by the method described under G-M Background, Page 309.
8. Determine the efficiency of this counting system by:

$$\text{Eff.} = \frac{\text{c/m observed} - \text{background}}{\text{d/m of standard}} = \text{Eff.}$$

$$\% \text{ Efficiency} = \text{Eff.} \times 100$$

9. Insert the unknown sample in the same geometrical location and count for at least 10 minutes or 10,000 counts. Determine the net counting rate, that is, sample counting rate minus the background counting rate.
10. To convert the net sample counting rate to d/m divide by the efficiency number:

$$\text{d/m} = \frac{\text{Net c/m of sample}}{\text{Efficiency}}$$

11. For accurate counting with a low relative error, the background of the counter  $c/m$  should be low compared with the sample  $c/m$ . A nomogram solution for the 0.9 and 0.95 error is given in Figs. G-2, G-3, and G-4. See the reference texts for information on accuracy of the counting as listed under "Statistical Fluctuation," "Probable Error," or "Statistics of Counting."
12. Once the  $d/m$  value of a sample is found, it may be converted into aerosol concentration, water concentration, curies, etc., as the problem requires.
13. Samples which are too high to count may be:
  - a. Moved to a greater distance from the detector. The efficiency at this location must be determined.
  - b. Cut in sections and counted.
  - c. Prepared for counting in an aliquot (if liquid) of lower specific activity.
14. Do not attempt to count samples that are dirty, flaky, or apparently contaminated with loose material. Such a sample may contaminate the counting system and raise the background or render the unit useless. If necessary, cover such samples (other than alpha emitters) with a thin foil such as Saran wrap, nylon, cellophane, or scotch tape.
15. Handle the samples with tongs when loading or unloading the counter.
16. Do not allow loose contamination or radiation sources to enter the counting area.
17. Record all data taken on a permanent counting-record sheet.

## **E. Sample-Counting Record Sheet**

The following instructions pertain to filling out the attached sample Counting Data Form, Page 316.

### **1. Across Top of Sheet**

- a. Counted by : Enter name.
- b. Scaler: The Serial Number of the unit used.
- c. Detector: The Serial Number of the unit used.
- d. Shelf: Note the shelf used. (Consider the shelf closest to the detector as number one.)
- e. Type of radiation: Circle the type of radiation being counted.
- f. Standard: Indicate the type and number of standard used.
- g. Activity: The d/m value of the standard.
- h. Date: Record the date of the counting.
- i. Overall efficiency: When the efficiency has been determined, record it in this space.

### **2. Columns**

- a. Sample: Record the sample-identification number so that later identification can be made with d/m value.
- b. Time: Record the time of start of count. This is required to correct for decay.
- c. Scale: Indicate the scale multiplier to be applied to the register reading.

Example: 32, 64, 128, 256 (binary),  
1, 10, 100, 1000, 100,000 (decade).

- d. Reg: Record the register reading indicated on the scaler.
- e. Register count: Record the product of the Columns;  
Reg. and Scale.

- |                         |                                                                                                                                                                                                                                                                                                     |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| f. Inter. Lights:       | The count indicated by the scaler-interpolation lights. Direct reading on decade scalars. Sum of lights lighted on binary scalars.                                                                                                                                                                  |
| g. Total Count:         | The sum of the columns; <u>Register count</u> and <u>Inter. Lights</u> .                                                                                                                                                                                                                            |
| h. Time Counted In:     | Record the time units such as minutes or seconds and the actual time period of count.                                                                                                                                                                                                               |
| i. Total Counting Rate: | The <u>Total Count</u> column divided by the column <u>Time Counted In</u> .                                                                                                                                                                                                                        |
| j. Background:          | Record the background in the same time units as Total Counting Rate.                                                                                                                                                                                                                                |
| k. Net Counting Rate:   | Subtract the <u>Background</u> column from the <u>Total Count Rate</u> Column.                                                                                                                                                                                                                      |
| l. Dis/___:             | Fill in the time units (min., sec., etc.) compatible with net counting rate units. Divide the net counting rate by the efficiency number and record the dividend as the dis/___.<br>(min., sec., etc.)                                                                                              |
| m. (0.9e):              | This value, the 0.9 error, is determined from tables, calculations or graphs. A nomogram for counting error is presented in Figs. G-2, G-3, and G-4. The counting error represents the range above and below the dis/___ value in which this sample would fall 90% of the time for repeated counts. |
| n. Remarks:             | Any facts that pertain to the sample counted (i. e., flaky, some of sample lost, etc.).                                                                                                                                                                                                             |

## F. Counting-Error Nomograms

The following nomograms (Figs. G-2, G-3, and G-4) allow the 0.9 and 0.95 error to be determined for various counting rates and counting times. As an example using Fig. G-2, for sample with an average rate of 1,250 c/m during a 4 minute counting period, upon repetition of the count there is a 90% probability of the average being within 29 c/m above or below 1250 c/m, or 95% probability of the average being within <35 c/m. The nomograms illustrated in Figs. G-3 and G-4 are used when the background is relatively high.



[illegible]

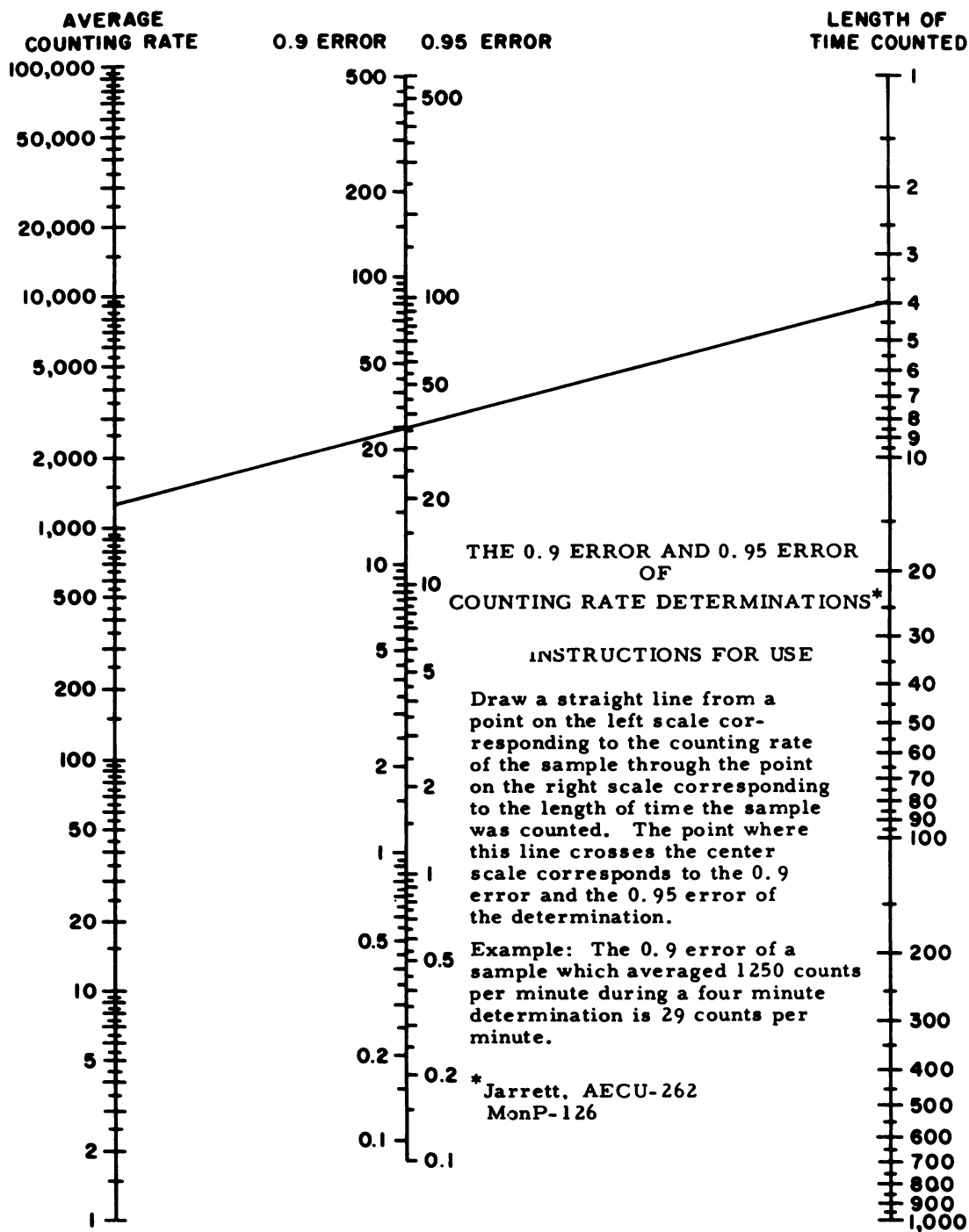


FIG. G-2

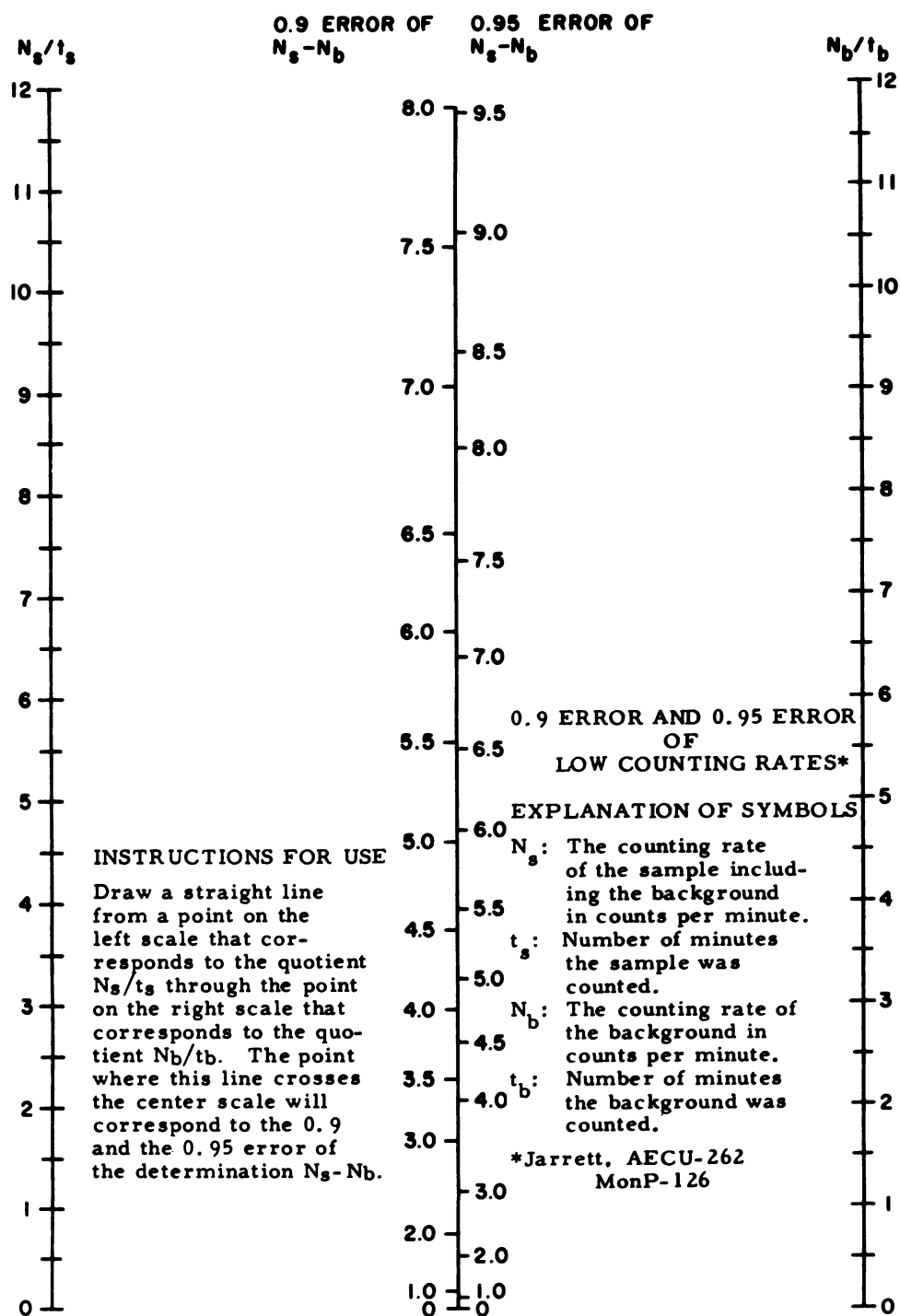


FIG. G-3

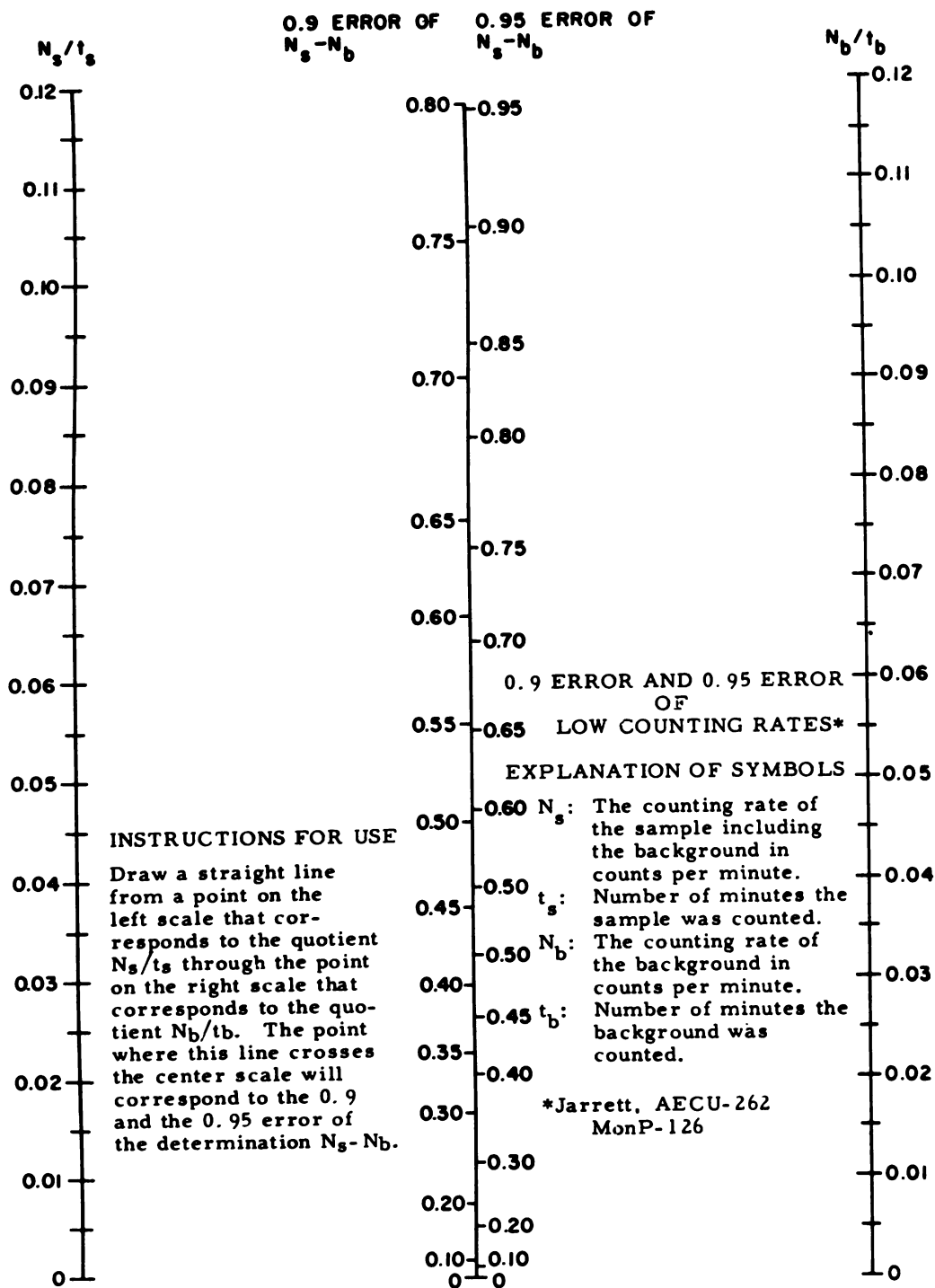


FIG. G-4

## APPENDIX G-2

### AEROSOL SAMPLING AND ANALYSIS

#### PURPOSE

The collection of an aerosol sample is basically the passing of air through a collection medium (filter paper) so that the collected particulate matter may be analyzed for radioactivity and an evaluation made as to the degree of health hazard, if any.

#### EQUIPMENT

The equipment required consists of a filter medium (generally paper, whose efficiency for the particular type of aerosol is known) and a suction unit (such as a vacuum cleaner or vacuum pump, with a known flow rate).

#### FILTER PAPER EFFICIENCY

The collection efficiency for some common filters are listed in Table G-1. These efficiencies were measured for the collection of particles of 0.3 microns diameter at a face velocity of 2.0 ft/sec. The efficiency increases for increasing particle size. The absorption factor of the filter media, caused by the penetration of the particulate matter in the filter medium, is normally zero for beta-gamma emitters and between 0.20 to 0.60 for alpha emitters. (The absorption factor for beta-gamma emitters is zero because the range of the beta-gamma radiation is greater than the thickness of the filter paper.)

TABLE G-1  
COLLECTION EFFICIENCIES FOR VARIOUS FILTER MEDIA

| FILTER         | PARTICLE DIAMETER IN MICRONS |         |         |         |         |              | RELATIVE<br>ALPHA<br>ABSORPTION |
|----------------|------------------------------|---------|---------|---------|---------|--------------|---------------------------------|
|                | Below<br>0.4                 | 0.4-0.6 | 0.6-0.8 | 0.8-1.0 | 1.0-2.0 | Above<br>2.0 |                                 |
| WHATMAN 41     | 23%                          | 28%     | 64%     | 74%     | 70%     | 100%         | 55%                             |
| WHATMAN 4      | 23                           | 32      | 38      | 79      | 74      | 100          |                                 |
| MSA TYPE "S"   | 48                           | 47      | 77      | 92      | 94      | 100          |                                 |
| H- 70 (18 mil) | 99.3                         |         |         |         |         |              | 40                              |
| CWS- 5         | 82                           |         |         |         |         |              |                                 |
| CWS- 6         | 99.9                         |         |         |         |         |              |                                 |
| GLASS FIBER    | 99.9                         |         |         |         |         |              | 20                              |
| MILLIPORE      | 99.9                         |         |         |         |         |              |                                 |

The flow rate may be determined by attaching an air flow meter or flow-rator of proper size to the suction side of the air sampler. The filter paper should be in place at the time of flow rate calibration.

## METHOD

Location of the sampler is important and, generally, it is placed in the area or space occupied by personnel. The sampler should be placed so that the air being sampled is the same as the air being breathed by the personnel involved. Extension hoses may be used for this purpose but this may reduce the air sampler flow rate, necessitating a recalibration of the air sampler unit. The filter medium is placed in the filter head or holder on the suction side of the sampler. Certain types of filter media are backed with a cloth weave for physical stability. Such filters should be placed in the holder with the exposed weave facing the holder support screen. Care must be taken at all times to prevent contamination of the filter medium in handling or storage, since any radioactive contamination found on the paper will be evaluated as an aerosol.

After inserting the filter, the sampler is started up on a carefully noted and logged schedule. The times of start and stop are noted since the total operating time in minutes, multiplied by the flow rate, will give the total volume of air collected by the sampler.

### Example:

Time stop                    1300

Time start                   1230

Total operating time - 30 minutes

Flow rate 10 cu. ft. per minute (cfm)

$30 \text{ min} \times 10 \text{ cfm} = 300 \text{ cu. ft. (total air sampled )}.$

Information should be recorded pertaining to the location of sample, conditions of operation, unusual incidents, personnel involved and any other pertinent data that may be useful in evaluating the significance of the aerosol activity.

## EVALUATION

Evaluation of a radioactive aerosol sample is accomplished by measuring the radioactivity on the filter medium with either a portable radiac counter or a laboratory counting system. For an accurate evaluation, laboratory counting is required. This method will be discussed first.

The MPC's for radioactive aerosols are generally given in microcuries per cubic centimeter ( $\mu\text{c/cc}$ ) (see Appendix A ). The activity of the aerosol sample, net counts per minute (c/m) on filter media, can be measured by laboratory counting equipment and converted to disintegrations per minute (d/m). The method for obtaining net d/m is explained in Part G-1 of this Appendix, "Counting Procedures."

Once the net d/m are determined from the counting, the aerosol concentration in  $\mu\text{c/cc}$  may be determined. Up to this point, the following information is known:

- a. Net d/m of the sample. (From counting.)

$$\text{Net d/m} = \frac{\text{c/m of sample} - \text{background}}{\text{Efficiency (of counter)}}$$

- b. Volume of sample in cubic feet.

Flow rate multiplied by operating time: Volume = (cfm) (T).

Volume in cubic centimeters = cubic feet  $\times 2.8 \times 10^4$  cc/cu. ft.

- c. Collection and absorption factor of filter media.

From Filter Paper Efficiency Table, G-1.

- d.  $1 \text{ d/m} = 4.51 \times 10^{-7} \mu\text{c}$

This information is substituted in the following formula:

$$\text{Concentration in } \mu\text{c/cc} = \frac{\text{d/m} \times 4.51 \times 10^{-7} \mu\text{c/d/m}}{\text{Volume (in cc)} \times \text{Eff (collection)} \times (1 - \text{absorption factor})}$$

Appendix A is a tabulation of the MPC's of radioactive materials in air. If the radioactive material is not known, the MPC's for unknown mixtures of radioactive materials listed at the end of Appendix A may be used.

## AEROSOL ACTIVITY ANALYSIS

When the radioactive aerosol has a very low MPC, the natural radioactive aerosol products in the air (radon and thoron) may mask the aerosol contaminant. These natural radioactive aerosols result from the decay products of the uranium and thorium minerals in the earth's crust. Uranium is the parent of radium, which in turn produces radon as a gaseous decay product.

The content of radon and thoron in the air will vary with locality and atmospheric conditions, such as rainfall, temperature, wind speed and direction, atmospheric pressure, etc. Radon and thoron undergo radioactive transformations, yielding active products of particulate form which are collected in the filter collection media. The uranium and thorium decay products whose presence will affect the count of the collected aerosol sample are radium A, B, C', and thorium A, B, C, C' and C''. The predominant aerosol decay product from the uranium series is radon, whose daughter, radium B, has a half-life of 26.8 min. The predominant decay product from the thorium series is thoron, whose daughter, thorium B, has a half-life of 10.6 hours. These decay products will influence both the alpha and beta-gamma analysis of the aerosol sample.

The decay curve of an aerosol sample may be considered as the sum of three decay curves: the radon daughters, the thoron daughters, and the contaminant. The decay curves for contamination due to long-lived activity are as shown in Fig. G-5 and may be evaluated by using the following calculation methods or by use of nomograms in Figs. G-6 and G-7. Once the long-lived activity is determined, the d/m value is used in the formula for finding  $\mu\text{c}/\text{cc}$ .

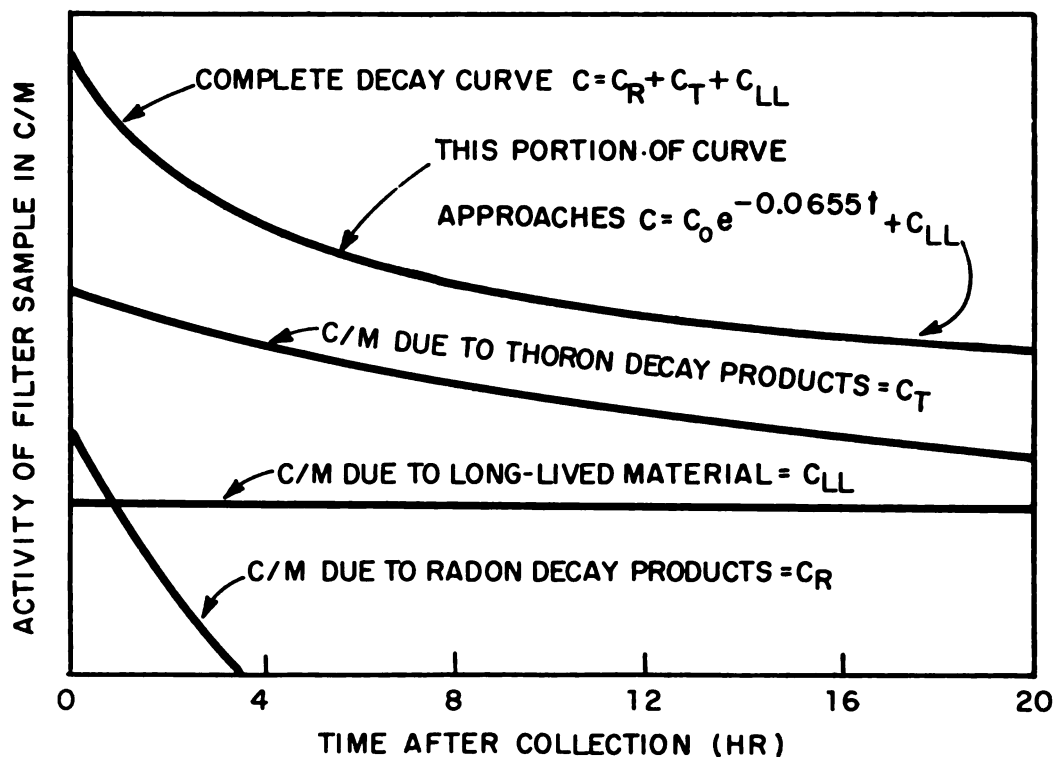


FIG. G-5 DECAY CURVES OF FILTER SAMPLE

#### A. Solution by Calculation

To evaluate the contribution to the long-lived activity, wait 4 to 6 hours. The count due to radon then becomes negligible and the curve will approximate the sum of  $C_{LL} + C_T$ . Its equation is:

$$C = C_0 e^{-0.0655t} + C_{LL}$$

where  $C_0$  is the original concentration of thoron, 0.0655 is the thoron decay constant and  $C_{LL}$  the long-lived contamination count.



Knowing two points on the curve, one can determine the value of  $C_{LL}$ . Two counts  $C_1$  at time  $t_1$  (4 to 6 hours after filter removal) and  $C_2$  at time  $t_2$  are taken. Separating these counts by a considerable interval reduces errors introduced into the results by counting fluctuations, incomplete radium chain decay products, etc. A convenient time for evaluation of the sample is 28 to 30 hours after the sample is collected.

Substituting  $C_1$ ,  $t_1$ ,  $C_2$ , and  $t_2$  in the above equation we get:

$$C_1 = C_0 e^{-0.0655t_1} + C_{LL}$$

$$C_2 = C_0 e^{-0.0655t_2} + C_{LL}$$

Solving simultaneously for  $C_{LL}$  where  $\lambda = 0.0655$

$$C_{LL} = \frac{C_2 e^{-\lambda t_1} - C_1 e^{-\lambda t_2}}{e^{-\lambda t_1} - e^{-\lambda t_2}}$$

$$C_{LL} = \frac{C_2 - C_1 e^{-\lambda \Delta t}}{1 - e^{-\lambda \Delta t}}$$

where  $\Delta t = t_2 - t_1$  in hours.

The contribution of short- and medium-lived activity can be detected by a high first count and subsequent plotting of their decays.

The methods of application of this analysis follow.

1. Immediate Count

An immediate count will be made on all air filters located in an area in which a spill or suspected escaping contamination occurs. This count would give an estimate of the concentration of activity if the contribution of the normal background is known.

2. 4 to 6 Hour Count

This count shows the activity in air minus the contribution due to radon. An abnormally high count here would be an indication of possible contamination.

3. 28 to 30 Hour Recount ( $\Delta t = \text{approx. 24 hours}$ )

Abnormal high counts would indicate contamination.

#### 4. Relation of $C_2/C_1$ to $a$ and $\Delta t$

In the equation

$$C_{LL} = \frac{C_2 - C_1 e^{-\lambda \Delta t}}{1 - e^{-\lambda \Delta t}}$$

we let  $e^{-\lambda \Delta t} = a$ ,

$$\text{then } C_{LL} = \frac{C_2 - C_1 a}{1 - a}$$

Now if  $C_{LL} = 0$

$$a = C_2/C_1$$

This relationship will give the ratio of second count rate to first count rate for uncontaminated air.

$$a = f(\Delta t) = C_2/C_1$$

The following table gives the values of  $a$ , for various  $\Delta t$ . Assuming  $C_{LL} = 0$ , the  $C_2/C_1$  ratio should not exceed these values.

| $\Delta t$<br>in hours | 20   | 21   | 22   | 24   | 25   | 26   | 27   | 28   | 29   | 30   |
|------------------------|------|------|------|------|------|------|------|------|------|------|
| $a$                    | .270 | .252 | .236 | .208 | .194 | .180 | .170 | .160 | .150 | .140 |

Solving for  $C_{LL}$  if  $C_2/C_1 > a$

If the ratio  $C_2/C_1$  is greater than  $a$ , then  $C_{LL}$  may be estimated by:

$$C_{LL} = \frac{C_2 - C_1 e^{-0.0655 \Delta t}}{1 - e^{-0.0655 \Delta t}}$$

Conversion  $C_{LL}$  in d/m to microcuries

$$\text{Concentration in } \mu\text{c/cc} = \frac{\text{d/m} \times 4.51 \times 10^{-7}}{\text{Vol (in cc)} \times \text{Eff (collection)} \times (1 - \text{absorption factor})}$$

$$(1 \text{ d/m} = 4.51 \times 10^{-7} \mu\text{c})$$

## B. Solution By Nomogram

$C_{LL}$  - the count due to long-lived activity

### Procedure:

1. Count the sample the first time no sooner than 4 hours after collection. This is the value  $C_1$ .
2. Wait at least 8 hours and count the sample again. This is the value  $C_2$ .
3. Determine the time difference in hours between count  $C_1$ , and  $C_2$ . This value is  $\Delta T$ .
4. Using Nomogram Fig. G-6 of this Appendix take a straight edge and connect a value equal to  $C_1$  on the line labelled  $C_1$  with a value equal to  $\Delta T$  (in hours) on the line labelled  $\Delta T$ . Read the value at the point where the straight line connecting  $\Delta T$  and  $C_1$  crosses the  $C_1 e^{-0.0655 \Delta T}$  line.
5. Subtract this number from  $C_2$ . This is value  $C_2 - C_1 e^{-0.0655 \Delta T}$
6. Go to Nomogram, Fig. G-7 of this Appendix, and draw a straight line from  $\Delta T$  to  $C_2 - C_1 e^{-0.0655 \Delta T}$ . Read the value of  $C_{LL}$  at the point when the straight line crosses the  $C_{LL}$  line.
7. This value of  $C_{LL}$ , when in d/m units, may be substituted in the formula:

$$\mu c/cc = \frac{d/m \times 4.51 \times 10^{-7} \mu c d/m}{Vol (in cc) \times Eff (collection) \times (1 - absorption factor)}$$

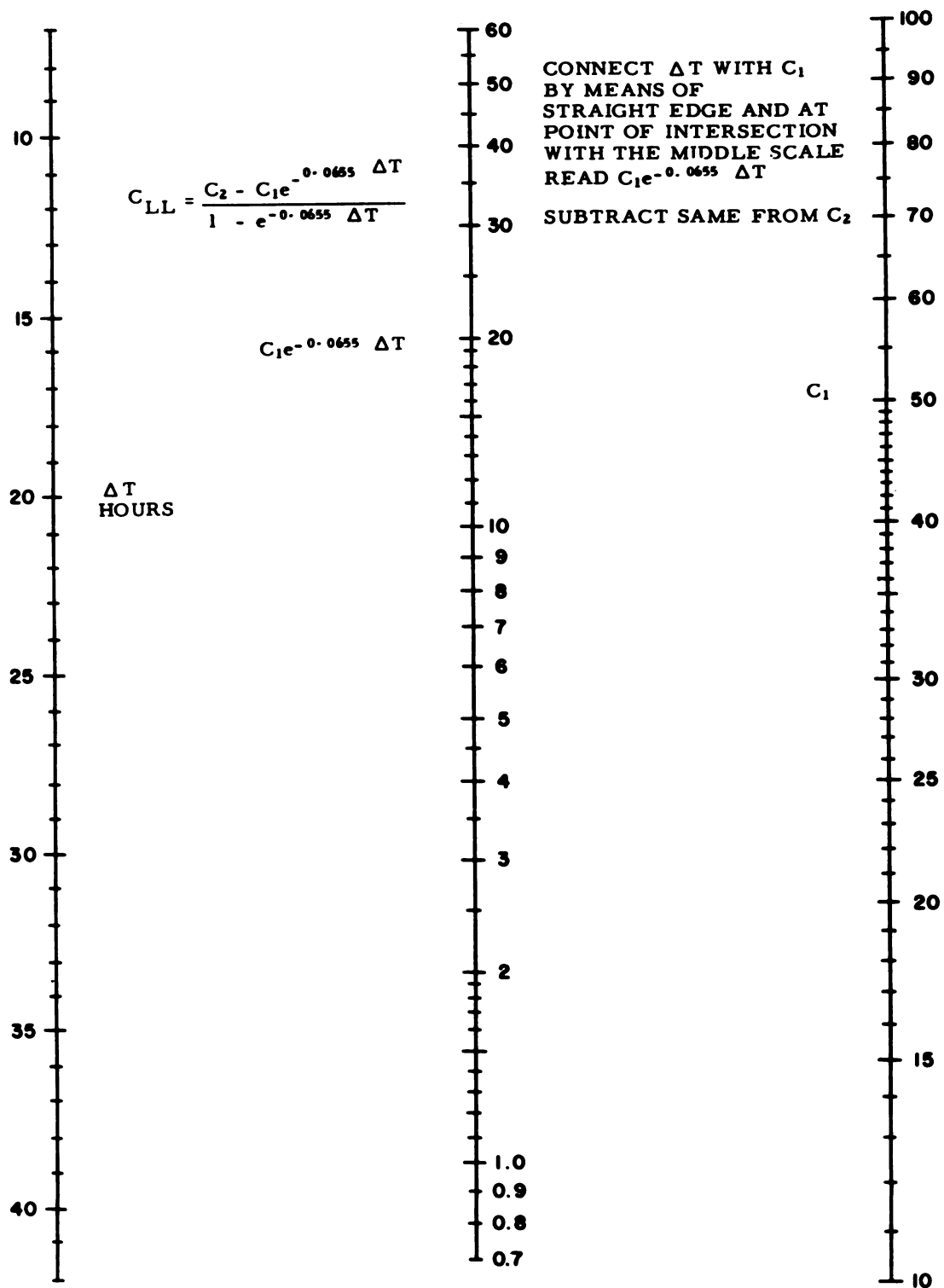


FIG. G-6

# NOMOGRAM FOR CALCULATING LONG-LIVED ACTIVITY

CONNECT  $\Delta T$  WITH THE DIFFERENCE OBTAINED FROM FIG. G-6 AND AT POINT OF INTERSECTION WITH THE MIDDLE SCALE READ  $C_{LL}$ .

$$C_{LL} = \frac{C_2 - C_1 e^{-0.0655 \Delta T}}{1 - e^{-0.0655 \Delta T}}$$

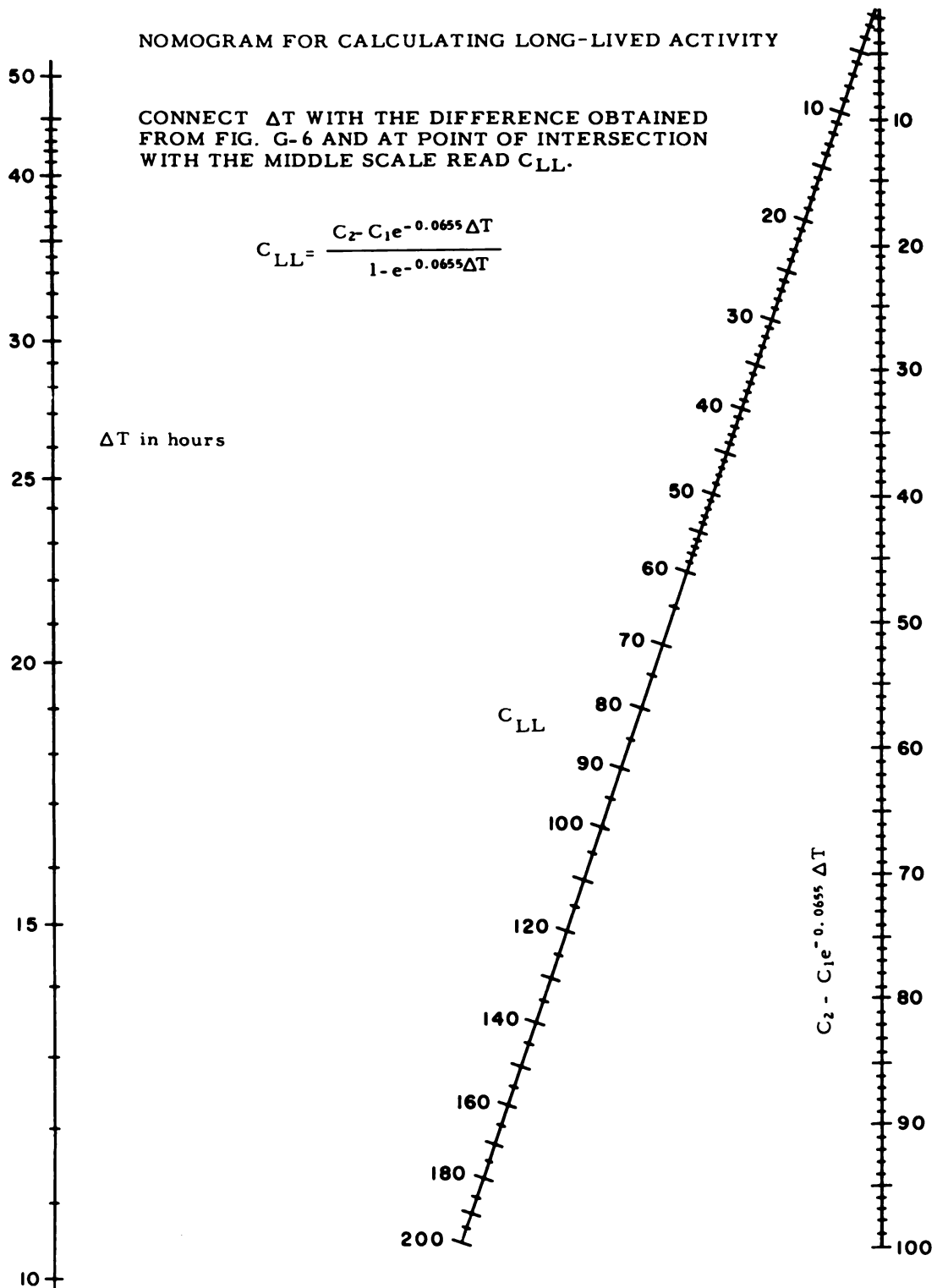


FIG. G-7

### C. Determination of Aerosol Concentration by Nomogram

#### Procedure:

1. Measure the activity level of the aerosol sample and correct for filter paper absorption and radon and thoron decay products as necessary.
2. Determine the total volume of air collected (cfm x time = volume).
3. Draw a straight line on Nomogram, Fig. G-8 of this appendix, between the value of total d/m of the sample and the value of the total volume. The point at which this line crosses the radioisotope concentration line is the  $\mu\text{c/cc}$  value.

### D. Determination of Aerosol Concentration By Portable Radiac - AN/PDR-27

The preceding methods of evaluation of an air sample require a laboratory counting system and also involve a certain time delay from the collection of the sample to the evaluation. In many cases the time delay is so long that another method of estimating the aerosol concentration is required. The beta-gamma aerosol concentrations within an area may be roughly determined by monitoring the collected sample with a portable radiac instrument.

Using the Westinghouse Portavac vacuum cleaner which has been converted to an air sampler (as shown in Fig. G-9) and a Navy radiac of the AN/PDR-27 series, the beta-gamma aerosol concentration may be measured as follows. The air sampler is loaded with a clean filter paper and operated in the area to be sampled for a 4 minute period. At a collection rate of 9 cfm, a 4 minute sample collects 36 cubic feet or one cubic meter. (35.4 cu.ft. equals 1 cubic meter or  $10^6$  cc.) An AN/PDR-27 series radiac will indicate beta-gamma activity if the probe is used with the window open and the instrument set on either the 0.5 mr/hr or 5 mr/hr scales. A net scale reading (scale reading of sample minus scale reading due to background) of 0.12 mr/hr is the equivalent of 0.01  $\mu\text{c}$  of beta-gamma activity while a net scale reading of 0.8 mr/hr equals 0.1  $\mu\text{c}$  and a net scale reading of 5.0 mr/hr equals 1.0  $\mu\text{c}$ . If a sample is collected for a period of 4 minutes and reads 5 mr/hr on the meter in an area of no background, the activity on the paper is 1.0  $\mu\text{c}$  of activity collected from  $10^6$  cc of air or a concentration of  $1 \times 10^{-6} \mu\text{c/cc}$ . Fig. G-9 is a typical calibration curve and monitoring position for a Portavac air sampler and the AN/PDR-27 series radiac.

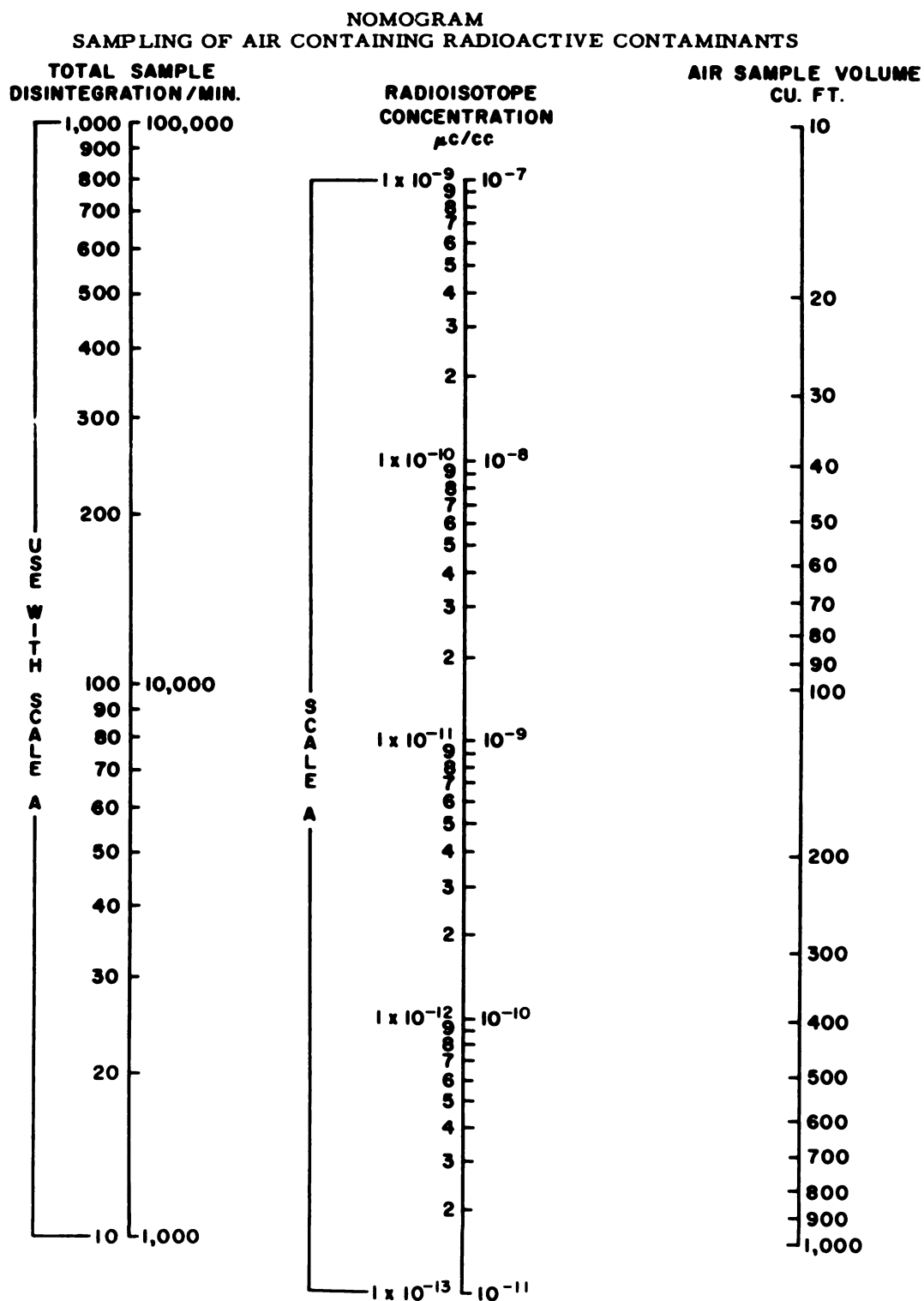


FIG. G-8

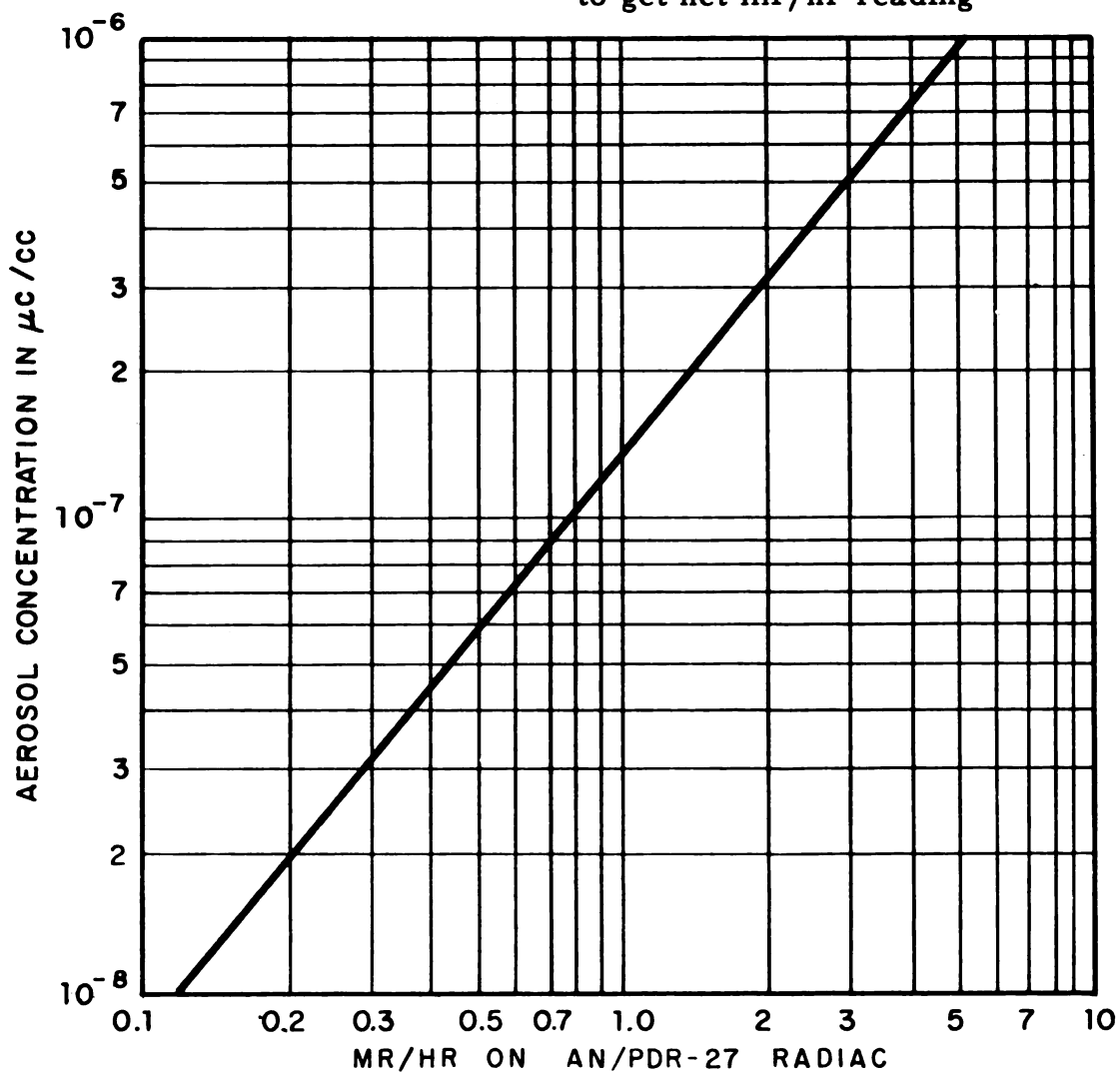
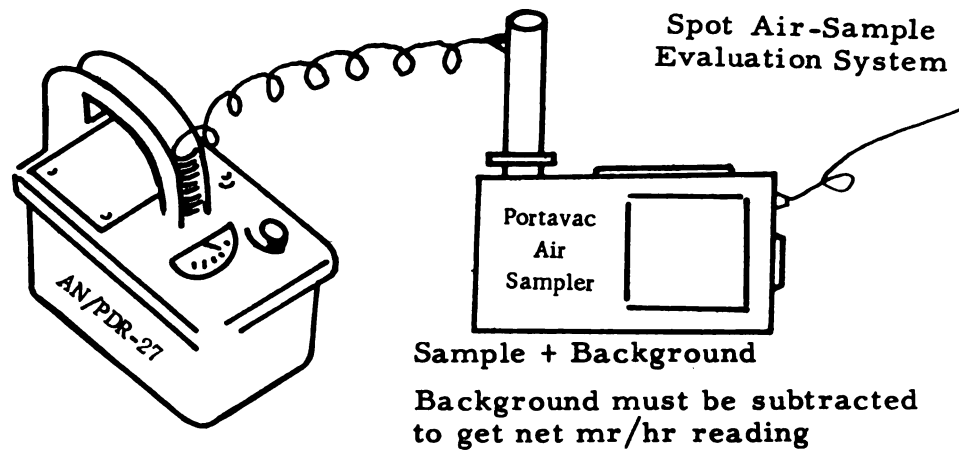


FIG. G-9 NET MR/HR (AN/PDR-27 RADIAC, WINDOW OPEN).  
SAMPLE READ IN FILTER PAPER HOLDER.



## APPENDIX G-3

### WATER SAMPLING AND ANALYSIS

#### PURPOSE

Water or liquid sampling may be performed for several reasons such as: to determine if water is potable, to determine if liquid may be released to uncontrolled sewage, etc. The objective of any liquid sampling and analysis is to determine if radioactive materials are present and, if so, in what quantity.

#### EQUIPMENT

To take a liquid sample, a container and sampling system are required. Both the sampling system and container must be free of contamination from any source other than the liquid being sampled. Once the sample is collected it is sealed and labelled, showing the sample location, time, date, and person collecting. Special counting systems can analyze liquid directly, but generally the sample must be prepared for counting by evaporation, or chemical techniques and evaporation. The residue of evaporation is mounted on a counting plate or planchet.

#### SAMPLE PREPARATION

A small measured volume (1 to 5 cc) of the liquid is placed onto a counting plate or into a cupped counting planchet and evaporated to dryness under a heat lamp or on a hot plate at low heat. Slow evaporation is desired to prevent spattering of the liquid.

For greater sensitivity, a larger volume of the liquid (up to one liter) may be placed in a beaker on a hot plate and boiled down to a 1 to 5 ml volume. This residue may be transferred to a counting planchet and evaporated to dryness.

Evaporation of liquids with high dissolved solid content, e.g., sea water, produces a very limited sensitivity of radioactivity detection due to the self-absorption of solids present in the dried sample. Often, in these cases, radiochemical techniques must be employed to isolate specific isotopes of interest.

#### EVALUATION

The sample, set on a planchet, is inserted in the counter and the general sample counting procedure previously discussed in Appendix G-1 is followed. Once the d/m value of the sample is determined, the concentration of the radioactivity in the sample may be determined by:

$$\text{Concentration } (\mu\text{c/cc}) = \frac{(\text{d/m}) 4.51 \times 10^{-7} \mu\text{c/dm}}{\text{Vol of sample counted (in cc)} \times \text{RE}},$$

where RE is recovery efficiency which should be known for accurate analysis. In cases of simple evaporation, RE can be taken equal to 1.

# **APPENDIX H**

## **SAMPLE QUESTIONS AND PROBLEMS**

The answers to the following questions are considered to be the minimum knowledge that each person involved in radiological safety work should possess. A large percentage of the questions concern general concepts and definitions, while others require simple arithmetical calculations. The concepts and definitions should be understood and usable by all radiological safety personnel without reference to a text. Radiological safety personnel involved in field tests and everyday uses of radioactive materials should be capable of performing the arithmetical calculations mentally.

### **QUESTIONS**

1. What is an isotope?
2. Are all isotopes radioactive?
3. The mass of the nucleus is less than the sum of the masses of the protons and neutrons added individually. The difference is accounted for by \_\_\_\_\_.
4. Is the loss of mass the source of the energy released in a nuclear detonation?
5. What does the term "half-life" mean?
6. Is the half-life the same for each radioactive isotope?
7. When is an isotope said to be radioactive?
8. What does Mev denote?
9. Define a curie.
10. Define radioactive decay.
11. What is fallout?
12. What type of ionizing radiations are released from a nuclear detonation?
13. What type of nuclear burst has the greatest contaminating potential?
14. What is the difference between initial radiation and residual radiation?

15. What is the difference between a radioactive object and a contaminated object?
16. Explain the difference between internal contamination and external ionizing radiation.
17. How may radioactive materials enter the body?
18. Define a roentgen.
19. What types of radiation may be measured in roentgens?
20. Define a rad.
21. Define a rem.
22. What is the relationship between rad and rem?
23. How does ionizing radiation affect a living organism?
24. Do all types of body tissue respond equally to a given type and dose of radiation?
25. Define radiosensitivity.
26. What does the term "relative biological effectiveness" mean when applied to ionizing radiation?
27. Define external radiation hazard.
28. Define internal contamination hazard.
29. Why is internal contamination such a serious problem?
30. What are the hazards from internal contamination?
31. What is the difference between an "acute exposure" and a "chronic exposure"?
32. What type of ionizing radiations are released from a nuclear detonation?
33. What is the present maximum weekly permissible exposure for total body exposure to ionizing radiations?
34. List four methods of controlling the dosage from external radiation.
35. Assume the following situation:

A person is exposed to a 100 r/hr gamma field, five feet from a source of cobalt 60.

  - a. Can this person become radioactive?
  - b. Can this person become contaminated?
  - c. When the person returns to a radiation-free area, is ionization from gamma radiations still taking place in his body?

36. Assume the following situation:

A person is working in an area with removable beta and gamma activity on various surfaces and tools.

- a. Can he become contaminated?
- b. Can he become radioactive?
- c. If he leaves the area, can he contaminate others?
- d. If he leaves the area, can he make others radioactive?
- e. Does his exposure to ionizing radiations cease when he leaves the area?

37. A man working in a radiation laboratory receives a 30 mr exposure of gamma each week for a period of 20 weeks. This exposure is considered to be:

- a. A sickness dose.
- b. A chronic dose.
- c. An LD-50 dose.
- d. An acute dose.

38. What is the MPE for whole-body exposure to penetrating radiations involving daily exposures over a long period of time?

39. Is an exposure to the chest considered a whole-body exposure?

40. What is the MPE for the forearms, hands, feet, and ankles for penetrating radiations involving daily exposure over a long period of time?

41. What is the MPE for radiation of low penetrating power involving daily exposure over a long period of time?

42. From radiations of low penetrating power, what portion of the body must be limited to an exposure of not more than 0.3 rem? How can this protection be accomplished?

43. Does the exposure from radiations of low penetrating power add to the whole-body exposure?

44. Does the exposure from penetrating types of radiation add to the MPE for whole-body surface exposure?

45. Assuming an MPE of 0.3 rem per week whole-body dose, how long must a person remain out of a radiation field to amortize a dose of 3 rem?

46. Exposure rate is:

- a. The total amount of radiation exposure received.
- b. The total amount of radiation exposure received in a week.
- c. The exposure per unit time.
- d. The amount of radioactive contamination per unit time.

47. Assume the following situation:

A man working in a field of 75 mrad/hr at five feet from a sealed source of cobalt-60 in an otherwise "Clean Area" receives a serious injury that requires medical attention including surgery.

- a. Should medical attention be given before any attention is given to the possibility of contamination?
- b. After medical attention has been given, what must be done with the medical equipment and space involved in the treatment?

48. Assume the following situation:

A man working in an area with loose contamination present received a wound from an object known to be highly contaminated. Serious bleeding results which requires medical attention.

- a. Should medical attention be given before any attention is given to the possibility of contamination?
- b. After medical attention has been given, what must be done with the medical equipment and space involved in the treatment?

49. Maximum permissible exposures are established for various types of operations such as field tests of nuclear devices and normal laboratory operations. Should work schedules be planned so that each person involved may receive the maximum permissible exposure?

50. What steps should be taken in the event of a "Radiological Accident" such as a major spill in which personnel are injured?

51. What is the purpose of Assessment, Delineation, and Control?

52. What is the Geiger plateau?

53. Why must an alpha counter have a thin screen over the window?

54. How are slow and fast neutrons detected?

55. What radiation measurements must be made to determine the activity of a sample?

56. What phenomena occur in a scintillation counter to detect ionizing radiation?

57. Why is it necessary to place a lead shield around the G-M tube in counting equipment?

58. What type of radiation is the pocket ionization chamber designed to measure?

59. How does a film badge indicate the dose due to ionizing radiations?

60. Film dosimeters (film badges) record radiation due to:
  - a. Background radiation.
  - b. Radiation received while worn in a contaminated area.
  - c. Radiation received when stored in an area.
  - d. All of the above.
61. One of the primary disadvantages of the film badge is the :
  - a. Relatively high cost.
  - b. Inability to read alpha.
  - c. Delay in obtaining readings.
  - d. Necessity of using a filter.
62. Will an AN/PDR-27 radiac detect beta radiation on the 500 mr/hr scale?
63. If the batt check position on the AN/PDR-TIB or AN/PDR-39 (ion chamber) reads properly, will the instrument respond to radiation?
64. Can the Cutie-Pie be zeroed in a radiation field?
65. Why must monitoring for alpha contamination be done with the probe of the PAC 3-G within about 1/4 inch of the surface, in question?
66. What are the three basic measurement techniques using portable monitoring instruments?
67. What may happen if a monitoring instrument is allowed to touch a contaminated surface?
68. List the nine items that must be recorded by a monitor.
69. Why is "record keeping" such an important part of the monitor's job?
70. A monitor should always wear :
  - a. Film badge.
  - b. Direct-reading dosimeter.
  - c. Protective clothing as required.
  - d. All of the above.
71. The importance of wearing self-reading pocket dosimeters when working in a radiation field is :
  - a. To replace the film badge dosimeter.
  - b. Only to supplement the film badge if it is lost.
  - c. To allow the wearer to estimate his dose during the progress of work.
  - d. To absorb the ionizing radiation.
72. What is the difference between a "Rapid or Gross Survey" and a "Detailed Survey"?

73. Does a gross survey of an area give detailed information on all contaminated areas?
74. During a gross survey:
- Personnel monitor only for hot spots.
  - Take air and water samples.
  - Make a quick systematic monitoring survey to evaluate the overall radiation situation.
  - Make a detailed plot of the radiation intensities in the area of interest.
75. During a detailed survey:
- Waist-high readings should be taken.
  - Wipe measurements for removable contamination are made.
  - Near-contact readings are made.
  - All of the above.
76. What are the advantages of:
- The constant-reading survey method?
  - The in-and-out survey method?
  - The aerial survey?
77. What is removable contamination?
78. How is it possible to detect removable contamination?
79. Why is air sampling necessary in an area that contains removable radioactivity?
80. What information is necessary for the analysis of an air sample?
81. Can radioactive gases always be detected by filter media?
82. If an air sample showed a concentration of alpha activity of an unknown isotope of  $2 \times 10^{-7} \mu\text{c/cc}$ , what type of respiratory equipment would be required?
83. What are the three "Don'ts" when working in contaminated areas?
84. When covered with protective clothing, where will contamination generally concentrate?
85. When is protective clothing monitored?
86. What functions are accomplished in a decontamination center?
87. How may radioactive contamination be removed from the surface of the body?
88. When performing skin decontamination, why should "hot spots" be cleaned before showering?

89. Why should medical assistance be requested when the skin starts to become red and sore during skin decontamination if the degree of skin contamination is high?
90. When monitoring personnel with a G-M type instrument, why is the window or shield on the tube open?
91. During personnel monitoring earphones are worn with the G-M type radiacs:
- a. Because the monitor can hear the increase in noise level produced by the G-M tube easier than he can read the meter.
  - b. To prevent contamination of the probe while watching the meter.
  - c. To allow the monitor to be more efficient.
  - d. All of the above.
92. If you had to decontaminate the breach mechanism of a 5 inch gun, would sandblasting be a permissible method? Why?
93. Is radioactive material destroyed in decontamination?
94. What is a "Radiological Clearance"?
95. How is a "Radiological Clearance" established?
96. What are the classifications stated in this manual?
97. What are the MPC's for Operational and Final Clearance for equipment?
98. What are the MPC's for Operational and Final Clearance for clothing?
99. What are the five "Rules of Thumb"?
100. Do the "Rules of Thumb" used in calculating decay rates, exposure rates, and total exposure from fission products give usable results by sacrificing some degree of accuracy?

#### **SAMPLE PROBLEMS AND ANSWERS**

1. If the dose rate from a Landing Craft (LC M) is measured as 100 r/hr at 1 day after the nuclear detonation, what will the dose rate be 4 days after the detonation? Ans: 25 r/hr (Rule of Thumb).
2. If the dose rate at a particular point 5 hours after an atomic detonation is 100 r/hr, what will the dose rate be at 35 hours after the detonation? Ans: 10 r/hr (use Thumb Rules).



3. Calculate the maximum exposure rate for a stay-time of 1/2 hour if the permissible exposure is 200 mr. Ans: 400 mr/hr.
4. A man enters a radiation field with his pocket dosimeter reading 30 mr. He works for 3 hours and notes that the pocket dosimeter reads 180 mr when he leaves the radiation area. What was his average exposure rate per hour? Ans: 50 mr/hr.
5. If the dose rate at 2 feet from a point source of radiation is 125 r/hr, what will the dose rate be at 10 feet from the source? Ans: 5 r/hr.
6. At H + 50 hr, a monitor reports that the average exposure rate is 750 mr/hr on a DD(destroyer). If the project team needs 2 hours to do a job, what would their estimated exposure be?  
Ans: 1500 mr (Rule of Thumb).
7. The PAC 3-G in operating order when held 1/4 inch above an extended Pu source of 60,000 d/m indicates 150 c/m on the meter dial with the range selector switch set on the X100 position. What is the efficiency of the instrument? Ans: 25%.
8. The same instrument (Problem 7) is taken to a contaminated area, and, with the probe 1/4 inch above the contaminated surface reads 400 on the meter with the selector switch set at X100 position. How many d/m per probe area does this represent?  
Ans: 160,000 d/m/probe area.
9. If a JUNO instrument 1/4 inch from a contaminated ground surface reads 40 mr/hr with all shields open and no beta or gamma radiation present, approximately how many micrograms per square meter ( $\mu\text{g}/\text{m}^2$ ) of plutonium are present? Ans: 80  $\mu\text{g}/\text{m}^2$ . (Use Fig. 4.6, Page 211.)
10. An air sampler was operated at 30 cfm from 1230 to 1250. Counting the sample, it was found that 10,000 d/m of plutonium was present. Neglecting losses in collector efficiency and absorption of alpha in the filter, compute the concentration of the radioisotope in the air. Ans:  $2.5 \times 10^{-10} \mu\text{c}/\text{cc}$ . (Use nomogram, Page 330.)  
  
If a man were to be exposed to this concentration of plutonium in the air during a decontamination operation for a period of 6 hours, would respiratory protection be required? Ans: No.
11. If a scaler has a background of 40 c/m and a calibration source of 10,000 d/m indicates total count of 10,000 counts in 10 minutes, what is the efficiency of the counter? Ans: 10%.









**(P O R A C C)**